COMPARISON OF HEAVY OIL VISCOSITY CORRELATIONS

by

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CERTIFICATION OF APPROVAL

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Approved by,

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(Iskandar bin Dzulkarnain)

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own as specified in the references and acknowledgements, and that the original work contained herein not been undertaken or done by unspecified sources or persons.

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(MUHAMMAD ABDUL KHOLIQ BIN AMAT JUPRI)

ABSTRACT

The modern practices of petroleum engineering is in the need of accurate predictions of reservoir phase behaviour properties in order to simulate and optimize other operations mostly production and processing operations. Among these reservoir fluid properties, viscosity is one of the most important properties especially during the design of pipelines, production and processing equipment, well testing, and also reservoir simulation. Using the direct measurement method to obtain the viscosity of the reservoir fluid requires a representative reservoir fluid sampling that is high in cost and it is often unavailable. In that case, the common procedure that is been using in the industry is using developed correlations as the main objective is to predict the viscosity of the crudes. However, the major problems with these developed correlations are focused in their extremely simplistic or complex nature that made their applicability decreases. Futhermore, in the case of heavy oil, they contain a large proportion of asphaltenes, waxes, and also other heavy components and so far, there are no prediction scheme has been capable of dealing with the mixtures successfully. Other than that, the commonly used correlations in predicting the viscosity, in the industry, were developed based on the data from a special regions or certain regions of the world only that limit their applications as a universal approach for viscosity estimation or prediction.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDY

World demands in energy resources have been increasing and encourage the industry of exploitation of oil and gas reservoirs to new development of technologies for unconventional resources, especially heavy oil reservoirs. These demands have put the modern petroleum engineering into several new challenges and these challenges include the requirement of an accurate reservoir phase behaviour properties in order to simulate and highly optimize the productions and processing operations. The knowledge of the required reservoir phase behaviour properties will results in optimum recovery of heavy oils. One property that yet made the recovery of heavy oils remains a challenge is the variations in their viscosity.

The viscosity of heavy oils is the one critical property in predicting oil recovery. It plays a very important role in other several process such as during the design of the pipelines, production and processing the equipments, well testing, and also reservoir simulation. The advantages of knowing the viscosity of the heavy oil reservoirs is thus very essential for a reliable and applicable in exploitation of reservoirs and also a big step in the development of new technologies and these goes to the good management decisions.

Predicting the viscosity of heavy oils is not an easy task to perform. Previous procedure [1, 2] in measurig the viscosity was using a direct viscosity measurement of the reservoir fluid that required a reservoir sample that is high in cost and often unavailable. This difficulty has made the industry to turn their heads into new practices of predicting the heavy oils viscosity by using developed correlations to achieve a reliable predicitions of heavy oil viscosity.

Researches has been made throughout the world in developing a reliable correlations to predict viscosity of heavy oil reservoirs in order to optimize resevoir production and maximize ultimate recovery and also to optimize production economics. In the past 60 years, many methods have been introduced by reserchers for predicting the viscosity of heavy oil. These methods include using a simple extrapolation, empirical correlations and also artificial intelligent.

1.2 PROBLEM STATEMENT

Viscosity is defined as the internal resistance to flow exerted by a fluid. Viscosity is an important physical property and parameter in the prediction of heavy oil viscosity. The oil viscosity is a strong function of temperature, pressure, oil gravity, gas gravity and gas solubility. The viscosity of heavy oil decreases rapidly with the effect temperature and with increasing concentrations of light components and can also vary over 2-3 order of magnitude during typical extrapolation and productions operations [3]. Attempting to get an accurate prediction of heavy oil viscosity is therefore very difficult.

In the previous researches, numerous numbers of viscosity-correlations and several algorithms have been introduced. Because of the complex composition of heavy oils and often undefined, there are no standard method of viscosity prediction in the industry [4]. It is also necessary to develop a viscosity correlation or model that is accurate and simple which will be easier than existing correlation or any other complex methods, less complicated computations for predicting the viscosity of heavy oils.

1.3 OBJECTIVES AND SCOPE OF STUDY

The objectives of this project are :

- To compare the heavy oil viscosity correlations for predicting the viscosity of heavy oil and highlight the most accurate correlations for heavy oil viscosity prediction.
- To improve the quality of viscosity prediction of heavy oil.

The scope of this study includes :

- Conducting research on the theories of viscosity prediction done by previous researches.
- Conducting a procedure to achieve the objective which is to compare previous heavy oil viscosity correlations.

CHAPTER 2
LITERATURE REVIEW

2.1 LITERATURE REVIEW

The study is focusing on comparing the heavy oil viscosity correlations published over the years and come up with the most accurate heavy oil viscosity correlation or model that can be used to estimate heavy oil viscosity. Basically, this literature will cover the fundamental theory and main concept that related to predict the viscosity of heavy oil.

2.1.1 Simple Mixing-Rule Prediction models

Previous study [5] have been examined that the sensitivity of numerical reservoir simulations to oil viscosity have proved that for oils of high viscosity, the uncertainty of the viscosity has a huge effect on the production rates calculation. A paper researching in viscosity prediction have introduced an analysis in using a simple mole-average power law based on Arrhenius equation and this concept has been used as a defalut method widely in some used thermal reservoir simulators to predict mixture viscosity [3].

The paper reported on testing the mole-average Arrhenius equation by comparing to a set of accurate benchmark data. The data used in developing the models cover a temperature range of -175^{o}C to 200^{o}C and extend to high pressures.

However, the results of using this method is far from ideal as the accuracy and reliability of this method for heavy oils have not been thoroughly tested.

2.1.2 Empirical Correlations

Basically, there are two approaches for predicting the viscosity of crude oil. The first approach is by using oilfield data, such as reservoir temperaturem produced oil API gravity, solution gas-oil ratio, [6, 7] to predict crude oil viscosity. The second approach uses the empirical and/or semi-empirical correlations that used other data for viscosity prediction such as reservoir fluid composition, pour point temperature, normal boiling point, and critical temperature [8-10].

Studies and reviews have been conducted to identified a number of correlations for predicting heavy oil viscosity. Based on a study [11] , these heavy oil viscosity correlations can be divided into three categories which are dead, saturated and undersaturated.

Another author did a study on this prediction of heavy oil viscosity correlation. In 1946, Beal presented a paper on dead oil viscosity correlation and introduced the correlation as a function of API gravity and temperature [6]. The author used 655 data points at temperature 100°F and 98 data points above 100°F.

In 1983, Egbogah and Ng has conducted a paper introducing two different correlations for predicting the dead oil viscosity [12]. The first correlation was a modified correlation from Beggs and Robinson (1975) and the second correlation was presented with a new parameter to estimate the dead oil viscosity which is the pour point temperature, $T_{p.}$

Recent study [13] introduced a fewer computations method for predicting the viscosity of heavy crude oil as a function of temperature and a simple correlation that can be used for heavy oil characterization. The proposed method from the study is exponential function by using the Vandermonde matrix which leads to well-behaved equations and enabling more accurate predicitions.

Several empirical correlations [14] used different techniques to predict the heavy oil viscosity. Some of them are obtained by using non-linear curve-fitting techniques.

Another method introduced in predicting the heavy oil viscosity is done by [15]. This study presented the development of an empirical model to predict viscosity based on the compositions of the gas by using regression technique.

Also, many correlations have been developed to predict the viscosity of oil at, below and above bubblepoint pressure. Beggs and Robinsons [16] have developed a correlations for viscosity prediction for dead-oil viscosity and gas-saturated oil viscosity.

In 1992, a paper has been presented by Labedi about a new set of correlations to predict dead, gas-saturated and undersaturated oil viscosity specifically from reservoirs in Libya [17]. Each of the equation was correlated as a function of data that are easily-obtainable such as API, P_r, and T_r. The data bank for the development of the correlations were consisted of approximately 100 laboratory analyses.

Another research has been conducted by Petrofsky and Farshad [18]. They developed a correlation for dead-oil, gas-saturated oil and alo undersaturated oil viscosity. They used a method by correlating the dead-oil oil viscosity as a function of API oil gravity and reservoir temperature whereas the gas-saturated viscosity as a function of dead-oil viscosity and also solution GOR. The undersaturated oil viscosity was correlated as a function of the gas-saturated oil viscosity , bubblepoint pressure and reservoir pressure.

A correlation was developed by using viscosity data collected from 35 North Sea [19]. The correlation gave a result of an error of 10%. In 2005, Naseri et al. had presented a set of correlations for dead, saturated and undersaturated crude oils from Iranian reservoirs [20]. In order to developed this set of correlations, an amount of 472 series of PVT date were used. The range for the API gravity and also crude oil viscosities that were used in the procedure of developing the correlations are 17°- 44° API and 0.75 – 54 mPa.s. The results of the study gave an average absolute error of between 2.12% to 16.4% for saturated and undersaturated viscosity prediction.

In 1959, Chew and Connally had proposed a new correlation in order to predict the gas-saturated oil viscosity, μ_{ol}. The gas-saturated oil viscosity was correlated as a function of dead-oil viscosity and also GOR. It is developed based on 457 crude oil samples collected from Canada, USA and South America.

A study has been presented on developing correlations for the gas-saturated oil and undersaturated oil viscosity [21]. The study was based on UAE crude oils. The author correlated the gas-saturated oil viscosity with solution GOR, reservoir temperature , gas specific gravity and also API oil gravity using only 57 data points whereas he developed the indersaturated oil viscosity correlation as a function of bubblepoint temperature , gas-saturated oil viscosity, reservoir pressure and solution GOR by using 328 data points. .

In 1980, Glaso presented a paper regarding a dead oil viscosity correlation by a procedure of analyzing 26 data points from six North Sea crudes [7]. The author did an adjustment to the API term for using the correlations with oils of different compositional natures.

Other than that, a correlation has been developed also for the dead-oil, gas-saturated oil and undersaturated oil viscositybased on Gulf of Mexicocrude oils and100 PVT laboratory reports [22]. The authors correlated the dead-oil viscosity with temperature and pressure and also solution GOR at bubblepoint pressure and API oil gravity/. The Gas-saturated oil viscosity was then correlated with the dead-oil viscosity and solution GOR, whereas the undersaturated oil viscosity was correlated with the gas-saturated, bubblepoint pressure, reservoir pressure and solution GOR.

Another correlation has been developed in order to predict the heavy oil viscosity. This correlation is known as LBC correlation [23]. It is the most widely used viscosity model used in reservoir engineering. It is used to tune the calculated viscosities by modifying the critical volumes of the C_{7+} components and/or the LBC correlation. It is very sensitive the the mixture density and to the critical volumes of the heavy components.

In 1987, Khan et al., published a study for viscosity correlations for saturated and undersaturated Saudi Arabian crudes [24]. The authors used specific gravity of oil instead of API gravity, relative temperature instead of temperature, solution gas ratio and flash gas specific gravity to predict the oil viscosity. The study gave a result of an error range of -20% to 20% when the correlations were tested against the data that was used to developed the correlations.

On a more current corresponding-states of viscosity models that give better prediction for oil viscosity, there is the Corresponding State Principle (CSP) [25]. The study concluded that the CSP is unsuited to simulate viscosities higher than approximately 10 mPa if the methane is used as a reference component.

From the literature reviewed earlier, it is noted that viscosity is very important property that need to be consider in order to achieve a successful exploitation in unconventional heavy crude oil without any difficulties. Predicting the viscosity gives an advantage in management decisions and production strategies. Many methods and studies have been introduced in the past years, all about improving the current technologies in predicting the heavy oil viscosity. These methods introduced because each and every methods have several disadvantages or limitations to be apply in all kind of situations that might occur in the way of predicting the viscosity. New improvements and technologies are encouraged to be introduced in the petroleum industry.

CHAPTER 3

METHODOLOGY

3.1 PROJECT METHODOLOGY

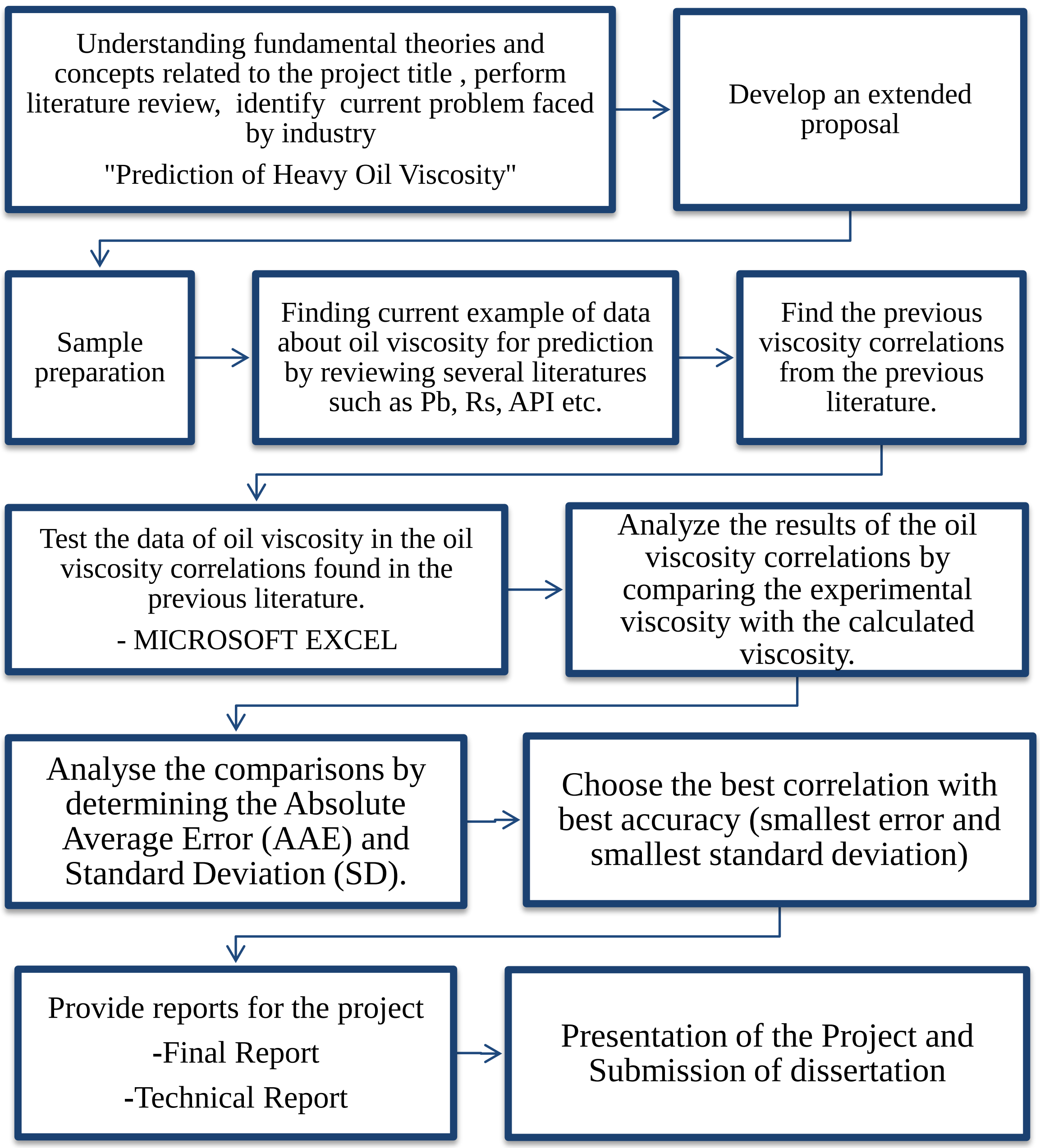


FIGURE 1. Process flow of work

3.2 KEY MILESTONE

Week	Objectives
	FYP I
5	Completion of preliminary research work
6	Submission of extended proposal
9	Completion of proposal defence
12	Confirmation on lab material and equipment for conducting experiment
13	Submission of Interim draft report
14	Submission of Interim report
	FYP II
5	Finalized the experiment procedure
6	Conducting experiment
7	Result analysis and discussion
8	Submission of progress report
9	Preparation for Pre-SEDEX
11	Pre-SEDEX
12	Submission of draft report
13	Submission of technical paper and dissertation
14	Oral presentation
15	Submission of project dissertation

TABLE 1 . Key Milestone for the Project

3.3 GANTT CHART

Table 2 below shows the proposed Gant chart for the project implementation for FYP II. Based on the Gant Chart, the project is feasible to be completed within the given amount of time.

No	Details	Weeks															
		1	2	3	4	5	6	7	MID SEMESTER BREAK	8	9	10	11	12	13	14	15
1	Finalized the experiment procedure																
2	Conducting experiment																
3	Result analysis and discussion																
4	Submission of progress report																
5	Preparation for Pre-SEDEX																
6	Submission of draft report																
7	Submission of technical paper and dissertation																
8	Pre-SEDEX																
9	Oral presentation																
10	Submission of project dissertation																

TABLE 2. Gantt Chart

CHAPTER 4

RESULTS AND DISCUSSION

Using the oil samples on Agip oils [26], 195 data points were used to test the accuracy of previous correlations to find viscosity of dead oil, bubblepoint oil or gas saturated oil and undersaturated oil. Table 6 shows the 195 oil samples came from the Mediterranean Basin, Africa, the Persian Gulf and the North Sea.

The correlations used has been selected based on previous studies and applications :

- Dead oil Viscosity correlation : *Beggs and Robinson's [16], Elsharkawy and Alikhan's [27], Glaso's [7], Kartoatmodjo and Schimdt's [28], Dindoruk and Christman's [22], Beal's[20], Labedi's [17], Petrosky and Farshad's [18], and Modified Egbogah and Jacks' for Heavy Oils[26].*

<u>Beggs and Robinson, 1975</u>

$\mu_{od} = 10^{X} - 1$

where, $X = y\, T_r^{-1.163}$

$y = 10^{Z}$

$Z = 3.3024 - 0.02023\gamma_O$

<u>Elsharkawy and Alikhan (1999)</u>[27, 29]

$\mu_{od} = antilog_{10}(x) - 1.0$

$x = antilog_{10}(y)$

$y = 2.16924 - 0.02525(API) - 0.68875[log_{10}(T_r)]$

<u>Glaso (1980)</u>[7]

$\mu_{od} = [3.141(10^{10})](T_r - 460)^{-3.444}[\log API]^{a}$

$a = 10.313[\log(T_r - 460)] - 36.447$

Kartoatmodjo and Schimdt (1991)

$$\mu_{od} = 16.0 \times 10^{8} \times T^{-2.8177} \times [log(API)]^{5.7527 \times log(T) - 26.9718}$$

Coefficients for the proposed μ_{od} correlation	
coefficient	Value
a_1	14.505357625
a_2	-44.868655416
a_3	9.36579 E+09
a_4	-4.194017808
a_5	-3.1461171 E-09
a_6	1.517652716
a_7	0.010433654
a_8	-0.000776880

TABLE 3. Coefficients for Kartoatmodjo and Schmidt's correlation

Beal (1946)[6, 20]

$$\mu_{od} = \left(0.32 + \frac{1.8(10^7)}{API^{4.53}}\right)\left(\frac{360}{T - 460}\right) a$$

$$a = 10^{\left(0.43 + \frac{8.33}{API}\right)}$$

Labedi (1992) [17]

$$\mu_{od} = \frac{10^{9.224}}{(API^{4.7013})({T_r}^{0.6739})}$$

Petrosky and Farshad (1995) [18]

$$\mu_{od} = 2.3511 \times 10^{7} \times {T_r}^{-2.10255} \times (\log API)^{X}$$

$$X = 4.5388 \times (\log T_r) - 22.82792$$

Modified Egbogah and Jacks for Heavy Oils (1990) [26]

$$\mu_{od} = 10^{X} - 1$$

$$X = 10^{[2.06492 - (0.0179 \times API) - (0.70226 \times \log T_r)]}$$

- Bubblepoint Oil Viscosity Correlations : *Beggs and Robinson's, Petrofsky and Farshad's [18], Almehaideb's [21]*, *Kartoatmodjo and Schimdt's* , *Dindoruk and Christman's*, *Chew and Connally [20], Labedi's (1992), Khan et. al[24]*, and *Elsharkawy and Alikhan's[29]*.

Beggs and Robinson (1975)[16]

$\mu_{ob} = A\mu_{od}{}^{B}$

$A = 10.715(R_s + 100)^{-0.515}$

$B = 5.44(R_s + 150)^{-0.338}$

Petrofsky and Farshad (1995) [18]

$\mu_{ob} = A\mu_{od}{}^{B}$

$A = 0.1651 + \left(0.6165 \times 10^{(-6.0866)\times(10^{-4})\times R_s}\right)$

$B = 0.5131 + \left(0.5109 \times 10^{(-1.1831)\times(10^{-3})\times R_s}\right)$

Almehaideb (1997)

$\mu_{ob} = (6.59927 \times 10^{5})R_s{}^{-0.597627}T^{-0.941624}\gamma_g{}^{-0.555208}API^{-1.487449}$

Kartoatmodjo and Schimdt (1991)[28]

$\mu_{ob} = -0.06821 + 0.9824 \times f + 0.0004304 \times f^{2}$

$f = (0.2001 + 0.8428 \times 10^{-0.000845\times R_s}) \times \mu_{od}{}^{(0.43+0.5165\times y)}$

$y = 10^{-0.00081\times R_s}$

Dindoruk and Christman (2004)

$$\mu_{ob} = A(\mu_{od})^B$$

$$A = \frac{a_1}{exp(a_2 R_s)} + \frac{a_3 {R_s}^{a_4}}{exp(a_5 R_s)}$$

$$B = \frac{a_6}{exp(a_7 R_s)} + \frac{a_8 {R_s}^{a_9}}{exp(a_{10} R_s)}$$

Coefficients of the proposed μ_{ob} correlation	
Coefficients	Value
a_1	1.000000 E+00
a_2	4.740729 E-04
a_3	-1.023451 E-02
a_4	6.600358 E-01
a_5	1.075080 E-03
a_6	1.000000 E+00
a_7	-2.191172 E-05
a_8	-1.660981 E-02
a_9	4.233179 E-01
a_{10}	-2.273945 E-04

TABLE 4. Coefficients for Dindoruk and Christman's correlation

Chew and Connally (1959) [20]

$$\mu_{ob} = 10^a\left({\mu_{od}}^b\right)$$

$$a = R_s[2.2(10^{-7})R_s - 7.4(10^{-4})] \qquad b = (0.65/10^c) + \left(0.25/10^d\right) + (0.062/10^e)$$

$$c = 8.62(10^{-5})R_s \qquad d = 1.10(10^{-3})R_s \qquad e = 3.74(10^{-3})R_s$$

Labedi (1992) [17]

$$\mu_{ob} = \left(10^{2.344-(0.03542\times API)}\right) \times {\mu_{od}}^{0.6447} \Big/ {P_b}^{0.426}$$

Khan et. al (1987) [24]

$$\mu_{ob} = \frac{0.09 \times \sqrt{\gamma_g}}{\left(\sqrt[3]{R_s}\right)(A^{4.5})(1-B)^3}$$

$$A = \left[(T + 459.67)\big/459.67\right] \qquad B = \left[141.5\big/(API + 131.5)\right]$$

Elsharkawy and Alikhan (1999) [29]

$$\mu_{ob} = A(\mu_{od})^B$$

$$A = 1241.932(R_s + 641.026)^{-1.12410}$$

$$B = 1768.841(R_s + 1180.335)^{-1.06622}$$

- Undersaturated Oil Viscosity Correlations (Ikiensikimama, et al. 2006): *Dindoruk and Christman, Almehaideb, Khan et. al [24], Petrofsky and Farshad, Vasquez and Beggs [30], Beal's[6], Labedi's (1992), Elsharkawy and Alikhan's [29] and Kartoatmodjo and Schmidt's [20].*

Dindoruk and Christman (2004)[22]

$$\mu_o = \mu_{ob} + a_6(P - P_b)10^A$$

$$A = a_1 + a_2 \log \mu_{ob} + a_3 \log R_s + a_4 \mu_{ob} \log R_s + a_5(P - P_b)$$

Coefficients for the proposed μ_o correlation	
Coefficient	Value
a_1	0.776644115
a_2	0.987658646
a_3	-0.190564677
a_4	0.009147711
a_5	-0.000019111
a_6	0.000063340

TABLE 5. Coefficients for Dindoruk and Christman's proposed correlation

Almehaideb (1997)[21]

$$\mu_o = \mu_{ob} \frac{P_r}{P_b}\left(0.134819 + \{1.94345 \times 10^{-4} R_s\} - \left\{1.93106 \times 10^{-9} {R_s}^2\right\}\right)$$

Khan et. al (1987)[24]

$$\mu_o = \mu_{ob} e^{9.6 \times 10^{-5}(P - P_b)}$$

Petrosky and Farshad (1995)[18]

$$\mu_o = \mu_{ob} + 1.3449 \times 10^{-3}(P - P_b).10^A$$

$$A = -1.0146 + 1.3322 \log[\mu_{ob}] - 0.4876[\log(\mu_{ob})]^2 - 1.15036[\log(\mu_{ob})]^3$$

Vasquez and Beggs (1980)[30]

$$\mu_o = \mu_{ob}(P/P_b)^m$$

$$m = C_1 P^{C_2} exp(C_3 + C_4 P)$$

Where C_1= 2.6 ; C_2= 1.187 ; C_3= -11.513 ; $C_4 = -8.98 \times 10^{-5}$

<u>Beal (1946)</u> [6, 20]

$$\mu_o = \mu_{ob} + 0.001(P - P_b)[0.024(\mu_{ob})^{1.6} + 0.038(\mu_{ob})^{0.56}]$$

<u>Labedi (1992)</u> [17]

$$\mu_o = \mu_{ob} - A[1 - (P/P_b)]$$

$$A = \frac{(10)^{-2.488}(\mu_{od})^{0.9036}(P_b)^{0.6151}}{10^{(0.01976 \times API)}}$$

<u>Elsharkawy and Alikhan (1999)</u> [29]

$$\mu_o = \mu_{ob} + (10^{-2.0771})(P - P_b)[(\mu_{od})^{1.19279}(\mu_{ob})^{-0.40712}(P_b)^{-0.7941}]$$

<u>Kartoatmodjo and Schmidt (1994)</u> [20]

$$\mu_o = 1.00081(\mu_{ob}) + \{0.001127(P - P_b) \times [-0.006517(\mu_{ob})^{1.8148} + 0.038(\mu_{ob})^{1.590}]\}$$

TABLE 6. Experimentally Measured PVT Data [26]

PVT Report	°API	Tr(°F)	Pr (psia)	Rs (scf/STB)	Pb (psia)	GG (av.)	OFVF	Vod (cp)	Vol (cp)	Vo (cp)
1	6	147.9	3428.75	231.46	2503.39	0.696	1.117	1386.9	295.9	354.6
2	6.3	165.2	5391.14	323.62	4021.96	0.675	1.146	561.1	90.3	108.3
3	6.5	210.2	4808.08	93.77	697.64	1.429	1.085	230	83.5	158
4	7.3	221.7	4732.66	18.82	249.47	1.134	1.057	211	177.4	345.8
5	7.5	153.5	3563.63	208.7	2082.77	0.756	1.107	1133.4	208.5	278.1
6	7.9	208.9	4148.14	25.48	342.29	1.477	1.067	236	151.8	269.5
7	7.9	165.2	5518.77	250.5	2902.25	0.768	1.127	443.7	106.1	149.9
8	8	215.6	4494.79	51.13	619.32	1.415	1.076	264.9	240	307.3
9	8	210.2	4708	103.1	658.63	1.491	1.059	230	118	205.5
10	8.2	215.6	4851.59	84.06	725.2	1.334	1.073	233.2	113	211
11	8.3	212	4883.5	89.27	639.63	1.47	1.076	262	116.3	190.1
12	8.6	217.4	4996.63	86.55	626.57	1.479	1.074	186	85.6	163.8
13	8.9	212	4908.15	69.57	597.56	0	1.067	219.2	106.3	192
14	9	210	4808.08	89.83	654.13	0	1.069	160.7	72.7	125.1
15	9.6	217.4	4895.1	108.54	967.42	1.129	1.088	117.2	49.2	75.2
16	10	154.8	2850.04	486.9	2665.84	1.236	1.235	116.3	12.2	12.6
17	10.5	152.6	2916.75	260	2076.97	0.815	1.148	112	24.7	27.7
18	10.9	154.2	2893.55	331.34	2802.17	0.81	1.184	115	19.7	20
19	11	167	5739.23	234.18	2588.96	0.735	1.11	438.1	87.7	126.3
20	11	152.6	2916.75	586.67	2916.75	1.253	1.302	125.2	8.3	8.3
21	11.2	154.8	2850.04	316.51	2546.9	0.812	1.174	105	19.8	21.4
22	11.4	153.1	2858.74	305.8	2622.32	0.776	1.161	110.6	21.5	22.8
23	12.4	210.2	4813.88	152.18	1763.69	0	1.124	98.7	35.3	52.4
24	12.4	152.6	2916.75	269.99	2432.32	0.714	1.135	133	21.8	23
25	12.6	208	2805.18	186.16	2233.62	0	1.132	88.1	23.3	28.9
26	12.8	215.6	4519.45	17.31	227.71	1.323	1.069	42.2	30.8	52.1
27	13.5	211.6	4410.67	201.53	1736.13	0	1.104	53.9	18.8	25.2
28	14	183.2	2552.7	40.97	1180.63	1.295	1.068	47.4	33.7	40.1
29	14.6	205.9	3684.02	41.92	337.94	1.178	1.085	158	65.4	109.2
30	14.9	207.9	3727.53	25.04	208.86	1.307	1.077	152.7	69.4	114
31	15.1	207.7	3727.53	25.21	227.71	1.344	1.078	152	69.9	111.9
32	15.2	214	3748.09	54.13	570.01	1.064	1.093	107.3	43.3	69
33	15.4	203	3665.16	21.49	355.35	1.276	1.072	163.6	74.6	123.4
34	16.6	131.4	1038.49	102.82	754.21	0.788	1.073	161.3	63.8	67.1
35	16	211.3	4281.58	338	3769.59	0.784	1.179	37.4	9.1	9.4
36	16.5	188.1	3328.67	97.32	697.64	1.188	1.086	43.7	21	28.4
37	16.8	140	1153.07	320.34	1074.75	1.517	1.146	112.6	28.4	29

38	17	250.7	7411.54	146.4	1082	1.232	1.153	10.1	5.6	14.5
39	17.6	194	4873.34	429.16	2236.52	0.934	1.268	23.4	4	4.9
40	18.8	244.4	7411.54	111.76	999.33	1.206	1.119	11.7	5.4	10.2
41	19	238.3	7047.49	113.7	1047.19	1.172	1.124	11.6	4.9	9.6
42	19	163.4	1806.47	188.82	952.91	1.292	1.115	50.9	16.9	19.8
43	19	217.4	6557.26	330.12	2319.19	0.914	1.234	23.9	7.3	11.3
44	19.2	165.2	1792.26	166.33	796.27	1.402	1.099	43.4	18.6	20.3
45	19.2	158	1563.12	109.93	469.93	1.412	1.078	49.3	27.2	34.6
46	19.3	154.4	1877.54	175.44	796.27	1.406	1.101	55.5	20.8	24.7
47	19.4	172.4	1649.98	177.83	825.28	1.411	1.112	41	18.4	19.9
48	19.5	240.8	7211.39	115.98	1038.49	1.059	1.124	7.7	4.6	9.7
49	19.5	177.8	1934.4	145.18	796.27	1.417	1.099	33	19.1	22.8
50	19.5	178.7	5305.56	332.61	1322.76	1.169	1.221	43.1	19	24.1
51	19.5	167	4238.07	25.37	256.72	1.105	1.059	28.1	22.4	36.5
52	19.6	231.8	6927.11	140.52	1209.63	1.092	1.129	11.1	5.6	9.7
53	19.7	170.6	1877.54	186.54	967.42	1.336	1.11	44.5	16.5	19.6
54	19.8	244	7137.42	135.47	1124.06	1.347	1.132	14.7	6.2	11.3
55	19.8	163.4	1806.47	167.89	896.35	1.333	1.108	47.2	18	21.2
56	19.8	150.8	1749.47	147.96	839.78	1.256	1.087	55.5	21.2	24.3
57	19.9	231.8	6856.04	121.64	1067.49	1.005	1.118	9.7	5.8	10.5
58	21	185.2	4873.34	500.23	2369.95	0.965	1.308	10.7	2.1	2.4
59	21.2	183.2	3721.73	404.01	2432.32	1.062	1.249	24.9	4	4.6
60	21.2	190.4	1209.63	27.76	213.21	1.421	1.07	11.2	8.8	10
61	21.3	188.8	3598.44	142.35	1009.48	0	1.097	16.4	6.7	9.2
62	21.3	179.6	6272.98	100.93	654.13	1.035	1.099	13.1	8.1	16.7
63	22	134.6	1749.18	640.25	1749.18	1.263	1.362	20.5	2.6	2.6
64	23.1	112.3	1315.51	141.02	796.27	0.83	1.062	69.8	35.9	40.7
65	23.3	276.8	3740.58	396.41	2674.54	1.218	1.276	3	1.2	1.4
66	23.7	176	4216.31	120.09	768.71	0.864	1.108	11.1	7.7	10.9
67	23.8	80.6	242.22	58.02	200.16	1.197	1.39	22.9	13.2	13.4
68	24.5	129.2	1520.02	8.61	107.33	1.53	1.034	45.2	24.9	36.1
69	24.5	162.5	1437.35	36.75	210.31	1.38	1.057	9.5	7.5	8.9
70	24.7	162.5	4011.81	162.67	1045.74	0.866	1.115	11.3	7.2	9.8
71	24.8	178.2	4281.58	116.26	796.27	0.932	1.099	13.4	8.5	12.6
72	25	262.4	3699.97	564.63	3100.96	1.28	1.393	3.7	1.1	1.2
73	25	117.5	1279.25	135.8	739.7	0.933	1.066	42.2	19.3	20.6
74	25.2	198.5	4381.66	323.68	1366.28	1.2	1.204	5.7	2.1	2.7
75	25.7	271.4	3698.52	484.29	2831.18	1.213	1.313	2.4	0.9	0.9
76	26	275	3713.02	578.51	3314.16	1.241	1.354	1.9	0.9	0.9
77	26.4	255.2	3669.51	643.58	3669.51	1.228	1.357	2.1	0.7	0.7

78	27	271	3713.02	595.05	3627.45	1.28	1.37	3.1	0.9	0.9
79	27.3	262.4	3710.12	591.17	3186.53	1.295	1.377	2.5	1	1.1
80	27.8	260.6	3691.27	629.86	3507.07	1.19	1.352	2.4	0.7	0.8
81	27.8	134.6	3826.16	702.32	3826.16	0.792	1.283	3.7	0.9	0.9
82	27.9	212	5533.28	686.33	2645.53	0.943	1.421	2.5	0.6	0.7
83	28	114.8	1166.12	225.74	1166.12	0.928	1.119	22.9	5.7	5.7
84	28.6	111.7	1293.76	131.58	654.13	0.93	1.068	21.8	14.2	15.7
85	28.6	111.2	1216.89	200.31	994.97	0.986	1.09	21.8	7.6	7.9
86	28.6	258.8	3726.08	763.66	3726.08	1.245	1.424	1.3	0.6	0.6
87	28.8	208.4	4822.58	416.73	1550.48	1.252	1.3	2.8	1	1.3
88	29	275	3676.76	667.28	3676.76	1.255	1.412	1.5	0.6	0.6
89	29	105.8	1579.49	233.4	1351.77	0.624	1.089	2.8	1.5	1.5
90	29.6	163.4	1459.1	245.28	1295.21	0.997	1.147	2.1	1.2	1.3
91	29.7	134.6	1927.58	89.22	384.36	1.156	1.07	4.9	3.1	3.6
92	29.8	128.1	1544.68	71.18	321.33	1.257	1.072	16.3	10.4	14.2
93	30.7	141.4	1419.94	289.14	1419.94	0.949	1.158	2.2	1.3	1.3
94	31	260.1	3713.02	781.99	3713.02	1.001	1.489	1.5	0.4	0.4
95	31	138.2	1501.16	259.22	1282.15	1.094	1.145	2.5	1.5	1.5
96	31.1	185	3755.09	756.67	3755.09	0.879	1.398	2.9	0.7	0.7
97	31.3	120.2	1337.27	55.19	171.15	1.218	1.057	11.2	7.9	9
98	31.6	242.6	3860.96	69.23	503.29	1.072	1.131	1.4	1.1	1.4
99	31.7	176	3499.82	785.26	3385.23	0.981	1.438	2.4	0.5	0.5
100	31.7	192.7	5405.64	1006.56	3862.42	0.884	1.562	1.5	0.4	0.4
101	33	219.2	3456.3	477.24	2483.08	1.051	1.276	2.1	0.8	0.9
102	33	211.1	5006.78	859.77	2713.7	0.914	1.503	1.1	0.3	0.4
103	33.8	192.7	5395.49	1256.95	4326.54	0.859	1.671	1.6	0.1	0.2
104	34.1	237.9	4467.23	704.54	4039.36	0.804	1.404	2.2	0.7	0.7
105	34.5	210.2	5293.96	516.83	2005.9	1.04	1.343	2	0.5	0.7
106	34.6	226.4	5135.87	108.76	839.78	0.794	1.125	5	3.6	5.2
107	35.1	154.4	2716.6	120.7	526.5	1.27	1.1	2.2	1.5	1.9
108	35.6	190.4	2944.31	852.05	2774.62	0.919	1.472	1.9	0.4	0.4
109	35.7	212	3562.18	136.02	661.38	1.095	1.151	1.4	0.9	1.2
110	36	118.4	384.36	105.04	384.36	1.137	1.082	2.7	1.9	1.9
111	36.2	140	5788.55	665.17	1891.32	1.057	1.383	2	0.8	0.9
112	36.6	118.4	351	72.12	327.79	1.077	1.06	2.6	2	2
113	36.6	116.6	478.63	56.96	369.85	1.157	1.055	2.7	2.1	2.1
114	37	222.8	4026.31	521.27	2375.76	1.011	1.336	1.6	0.5	0.6
115	37	221	3328.67	773.38	2858.74	1.05	1.495	1.8	0.4	0.4
116	37	186.8	4879.15	1021.05	2809.42	0.902	1.591	1.2	0.3	0.4
117	37.2	152.6	2423.62	495.45	1607.04	1.054	1.291	2	0.7	0.7

118	37.2	180.5	2588.96	432.6	2517.89	0.797	1.239	2.9	1.1	1.1
119	37.2	300.9	6248.32	1396.86	6088.78	0.749	1.793	1.2	0.3	0.3
120	37.2	190.4	3215.54	871.65	3037.14	0.92	1.492	1.7	0.4	0.4
121	37.2	269.6	5697.17	1081.29	4243.87	0.866	1667	1.8	0.4	0.4
122	37.2	176	4873.34	1365.21	3753.64	0.927	1.727	1.2	0.4	0.4
123	37.2	300.9	6248.32	1396.86	6088.78	0.749	1.793	1.2	0.3	0.3
124	37.4	150.8	2503.39	417	1351.77	1.268	1.251	2.1	0.8	0.9
125	37.5	146.3	3103.86	576.95	2574.46	0.909	1.306	5.3	1.4	1.5
126	37.5	303.1	6301.99	550.92	6272.98	0.764	1.86	1.4	0.3	0.3
127	37.5	271.4	5482.51	866.21	3652.11	0.919	1.557	1.5	0.4	0.5
128	37.7	305.1	6613.82	1654.36	6613.82	0.738	1.939	1	0.5	0.5
129	37.8	145.4	2423.62	234.01	783.22	1.416	1.154	1.8	1	1.2
130	37.8	231.8	5349.08	1467.2	4737.01	0.861	1.831	1.3	0.4	0.4
131	37.9	228.2	4345.4	1357.94	4267.08	0.855	1.58	1.2	0.3	0.3
132	38	171.5	3114.01	583.01	2687.59	0.936	1.322	4.3	1.1	1.1
133	38	257.7	13242.15	363.7	1670.86	1.113	1.303	1.3	1	1.4
134	38.4	224.6	4104.63	711.2	2924.01	0.896	1.435	1.6	0.4	0.5
135	38.5	224.6	3684.02	1134.14	3527.37	0.923	1657	0.9	0.3	0.3
136	38.5	204.8	3215.54	725.86	2496.14	0.983	1.441	1.9	0.4	0.4
137	38.8	152.6	2423.62	475.41	1493.91	1.109	1.27	1.8	0.6	0.7
138	38.8	238.1	5305.56	645.41	3456.3	0.782	1.392	2.3	0.7	0.9
139	38.8	183.2	2271.33	524.1	1863.76	4.46	1.27	1.5	0.7	0.7
140	39	271.4	6187.41	763.39	3243.09	1.025	1.483	1.4	0.4	0.5
141	39	194	2233.62	436.43	1721.62	1.464	1.242	1.4	0.6	0.6
142	39.4	181.4	3370.73	533.87	2062.47	1.057	1.326	1.2	0.5	0.5
143	39.6	292.1	6299.55	1700.94	5868.32	0.788	2.047	0.9	0.2	0.2
144	39.7	325.4	14466.29	387.52	2219.11	0.939	1.368	0.6	0.3	0.6
145	40	158	3079.2	217.47	511.99	1.349	1.187	1.5	0.9	1.2
146	40	303.1	6336.8	1585.4	5959.69	0.752	1.886	1.2	0.3	0.3
147	40	334.4	14913.01	444.49	2140.79	1.136	1.412	0.6	0.3	0.7
148	40	334.4	14863.7	410.79	2133.54	1.095	1.372	0.6	0.3	0.6
149	40.1	302	5888.62	1760.56	5760.99	0.924	1.923	1.2	0.5	0.5
150	40.4	252	5518.77	233.24	1276035	0.985	1.226	1.6	1	1.5
151	40.6	269.6	6358.55	1253.73	4565.86	0.861	1.761	1.9	0.4	0.6
152	40.8	186.8	4739.91	912.73	2657.13	0.972	1.568	1.4	0.3	0.4
153	41	180.5	3369.28	529.15	1834.76	1.047	1.321	1	0.4	0.4
154	41	266	4992.28	1559.47	4992.28	0.663	1.916	0.8	0.2	0.2
155	41	287.6	6747.26	1575.35	5675.42	0.763	1.918	1	0.2	0.3
156	41	277.2	6528.25	1398.8	5106.86	0.826	1.832	1.5	0.3	0.3
157	41.1	296.6	6898.1	1717.76	5760.99	0.82	2.071	1	0.2	0.2

158	41.2	159.8	2760.11	913.18	2760.11	0.993	1.505	1.8	0.5	0.5
159	41.5	226.4	4267.08	1306.64	3684.02	0.977	1.847	1.1	0.2	0.2
160	41.5	159.8	3420.04	769.83	2603.47	0.872	1.426	1.9	0.5	0.6
161	41.5	302	7147.57	1555.36	5589.84	0.818	1.98	1.1	0.2	0.3
162	41.5	153.8	3655.01	1405.19	3655.01	1.027	1.68	1.9	0.3	0.3
163	41.5	235.4	5433.2	1657.52	4850.14	0.901	1.96	1.1	0.2	0.2
164	41.7	167	3272.1	963.03	2702.1	0	1.516	1.5	0.4	0.4
165	41.7	167	3032.79	1046.87	2944.31	0.895	1.582	1.5	0.3	0.3
166	42	201.2	4124.94	1746.29	3968.29	0	1.967	0.8	0.2	0.2
167	42	165.7	3480.96	1206.98	3362.03	0.857	1.657	1.5	0.3	0.3
168	42	287.6	6747.26	1897.08	5788.55	0.81	2.1	0.9	0.2	0.2
169	42.2	167	3201.03	1099.33	3201.03	0.953	1.58	1.5	0.3	0.3
170	42.4	341.6	15304.62	690.16	2578.81	1.045	1.572	0.5	0.2	0.4
171	42.5	150.1	3295.31	641.47	1517.12	1.113	1.394	1.9	0.7	0.8
172	42.5	167	3612.95	884.58	2631.03	0.995	1.505	1.7	0.4	0.4
173	42.5	167	3567.98	942.99	2660.03	0.885	1.5	1.5	0.4	0.4
174	42.5	167	3663.71	931.61	2944.31	0.893	1.459	1.6	0.2	0.2
175	42.5	167	3612.95	1113.66	2944.31	0.991	1.605	1.8	0.4	0.4
176	42.6	167	3314.16	1165.01	3214.09	0.945	1.62	1.6	0.3	0.3
177	42.8	253.4	4024.86	1390.75	3968.29	0.928	1.846	0.7	0.2	0.2
178	43	222.8	5589.84	708.53	2120.48	1.007	1.517	1.2	0.1	0.2
179	43	154.4	1601.24	356.21	1045.74	1.292	1.201	0.9	0.5	0.6
180	43.5	167	3612.95	1264.28	3441.8	0.913	1.618	1.4	0.2	0.2
181	43.6	159.1	3498.36	941.05	2488.89	0.861	1.528	1.7	0.6	0.6
182	43.6	197.6	3044.39	1593.4	2760.11	1.016	1.985	1.2	0.2	0.2
183	44	277.9	6521	1678.62	5705.87	0.847	1.937	1.1	0.2	0.3
184	44.5	289.4	6433.97	1404.3	5170.68	0.795	1.874	1.1	0.3	0.5
185	44.9	296.6	6898.1	3298.66	6358.55	0.775	2.887	0.9	0.1	0.2
186	45	276.8	6510.85	1664.63	5697.117	0.85	1.941	1	0.2	0.3
187	45.4	225.5	5064.8	971.75	4523.8	0.695	1.519	1	0.4	0.4
188	45.5	231.4	4793.57	2323.75	4082.88	0.968	2.428	0.7	0.2	0.2
189	46.9	90.5	1644.75	365.76	1380.78	0.959	1.174	1.5	0.7	0.7
190	47	140	2517.89	121.81	147.94	1.789	1.129	1.8	1	1.1
191	49.2	172.4	3769.59	1617.27	3161.87	0.928	1.913	1	0.2	0.3
192	50.9	183.9	2658.58	367.48	661.38	1.408	1.341	0.8	0.4	0.4
193	51	226.8	5974.2	2987.14	4210.51	0.881	2.805	0.8	0.1	0.1
194	53	237.2	5956.79	2191.33	3826.16	0.883	2.478	0.5	0.1	0.2
195	56.8	140.7	1170.47	300.91	1170.47	0.649	1.185	0.5	0.4	0.4

4.1 DATA GATHERING AND ANALYSIS

The testing of the correlations divided in three type of oil viscosities which are dead oil, gas-saturated or bubblepoint oil and undersaturated oil viscosities. Oil samples have been divided into three different API gravity classes : **extra-heavy oils for °API ≤ 10, heavy oils for 10<°API ≤ 22.3, medium oils for 22.3 < °API ≤ 31.1 and light oils for °API > 31.1** [26].

Dead Oil Viscosity Correlations

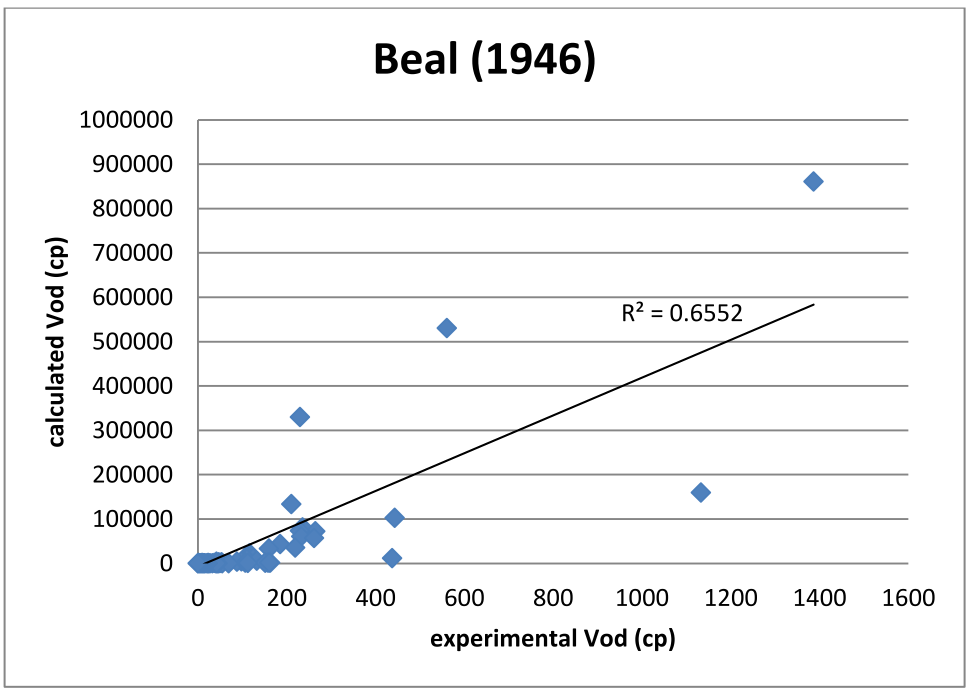


FIGURE 2. Beal's correlation for dead oil viscosity

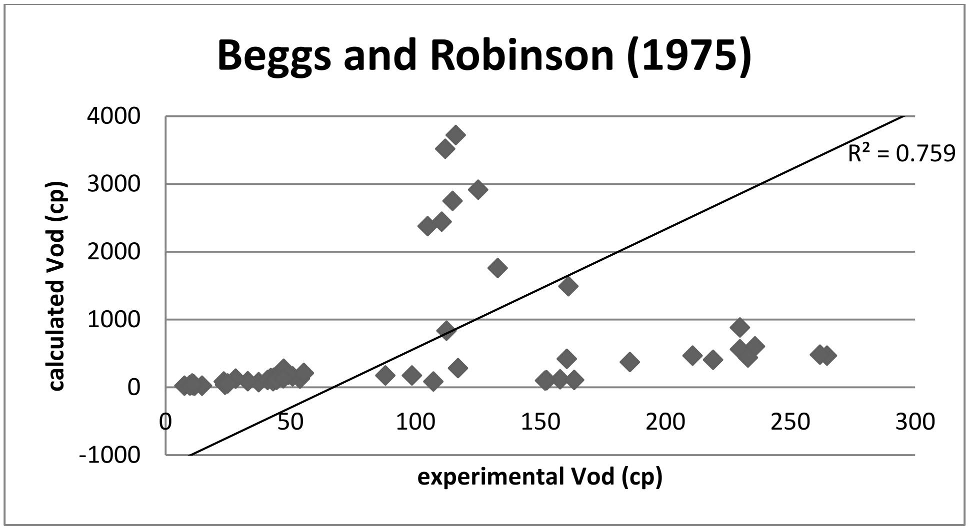


FIGURE 3. Beggs and Robinson's correlation for dead oil viscosity

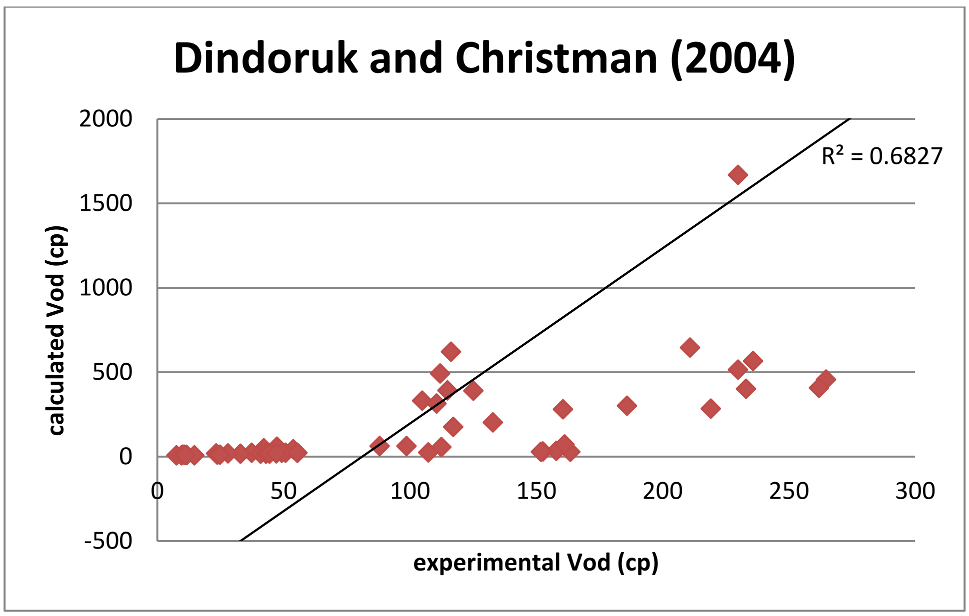


FIGURE 4. Dindoruk and Christman's correlation for dead oil viscosity correlation

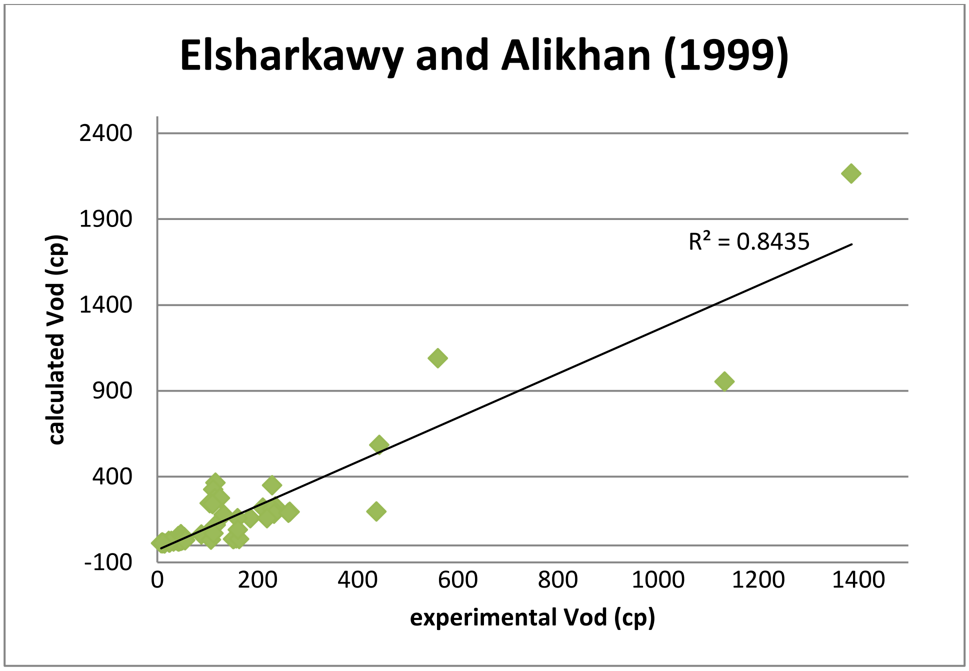


FIGURE 5. Elsharkawy and Alikhan's correlation for dead oil viscosity

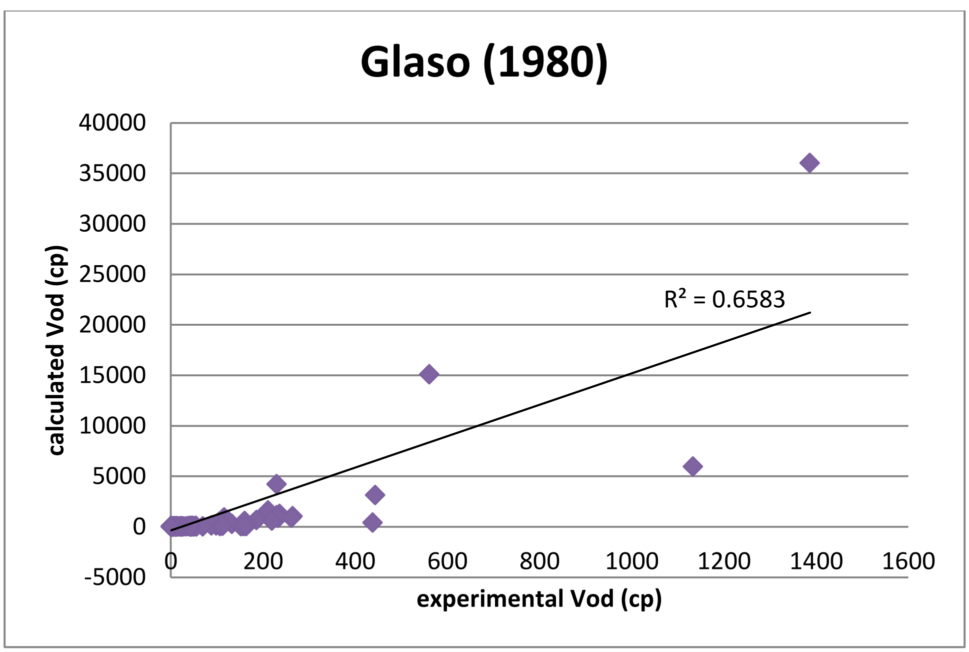


FIGURE 6. Glaso's correlation for dead oil viscosity

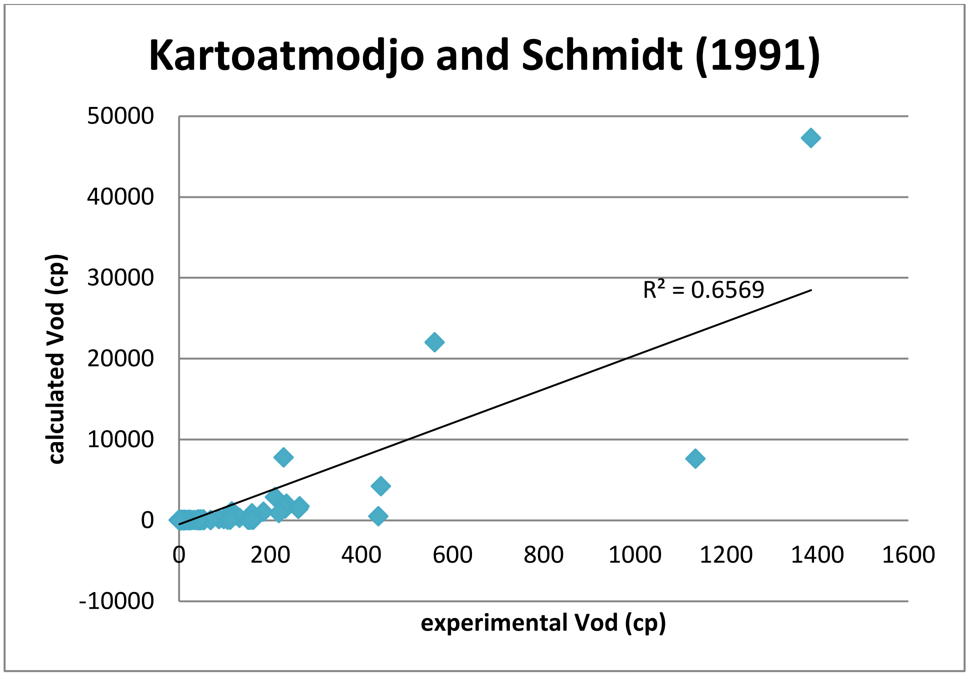


FIGURE 7. Katoatmodjo and Schmidt's correlation for dead oil viscosity

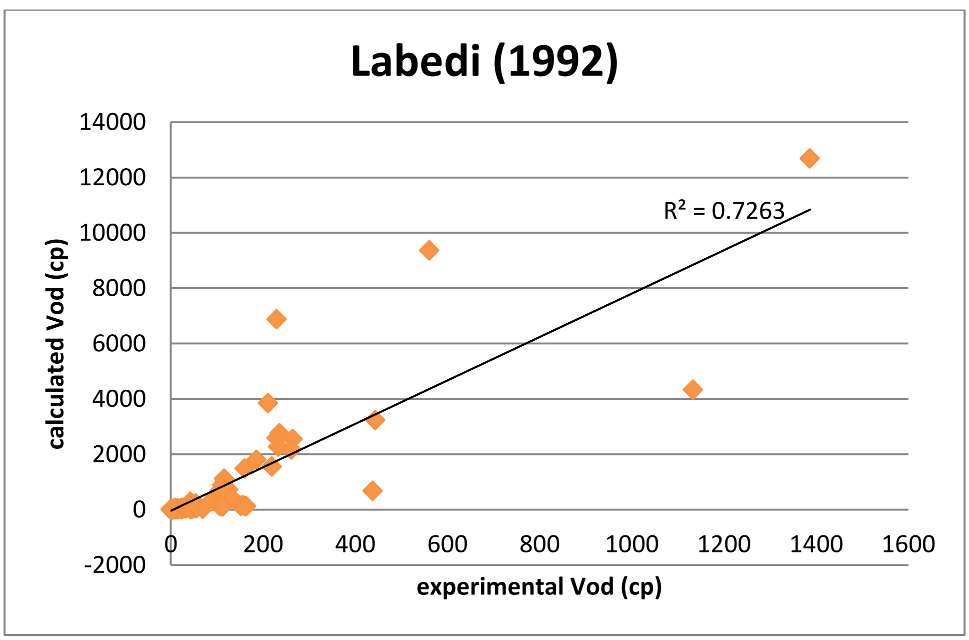


FIGURE 8. Labedi's correlation for dead oil viscosity

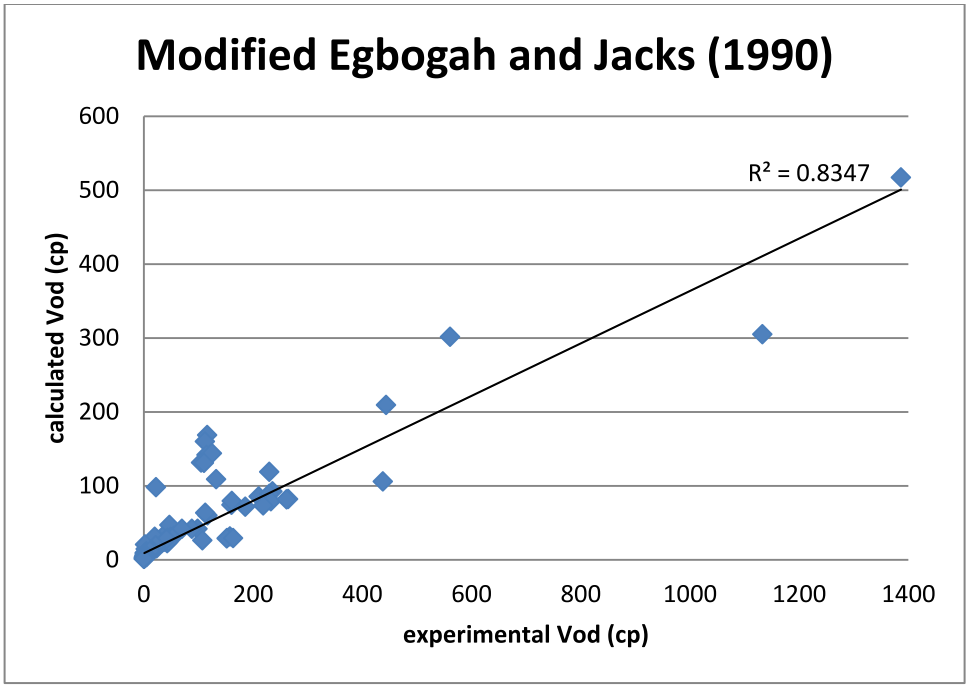


FIGURE 9. Egbogah and Jacks' modified correlation for dead oil viscosity

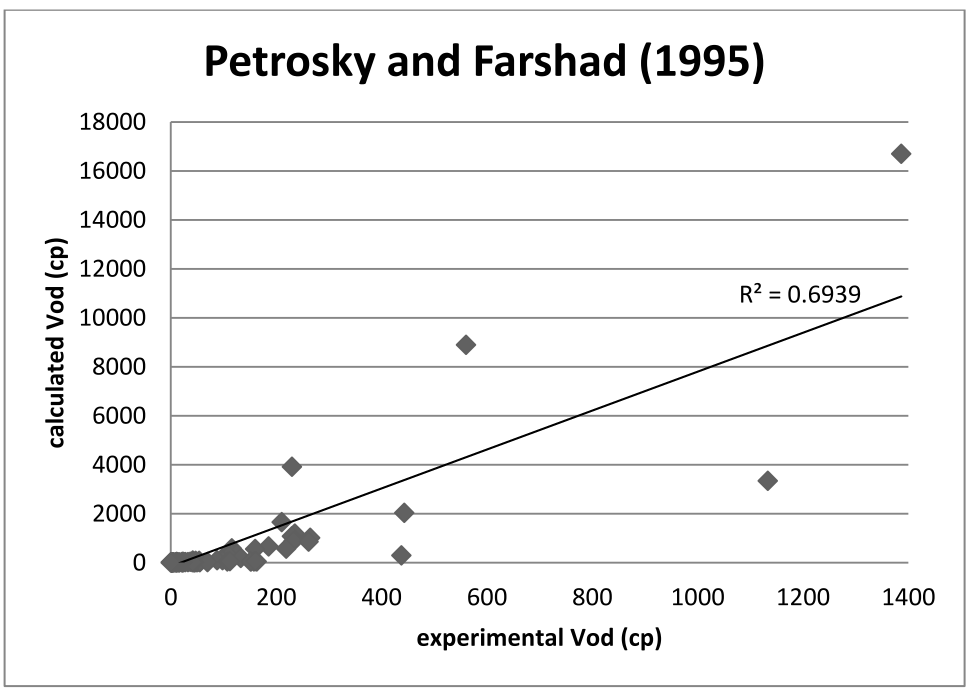


FIGURE 10. Petrosky and farshad's correlation for dead oil viscosity

Bubblepoint Oil Viscosity Correlations

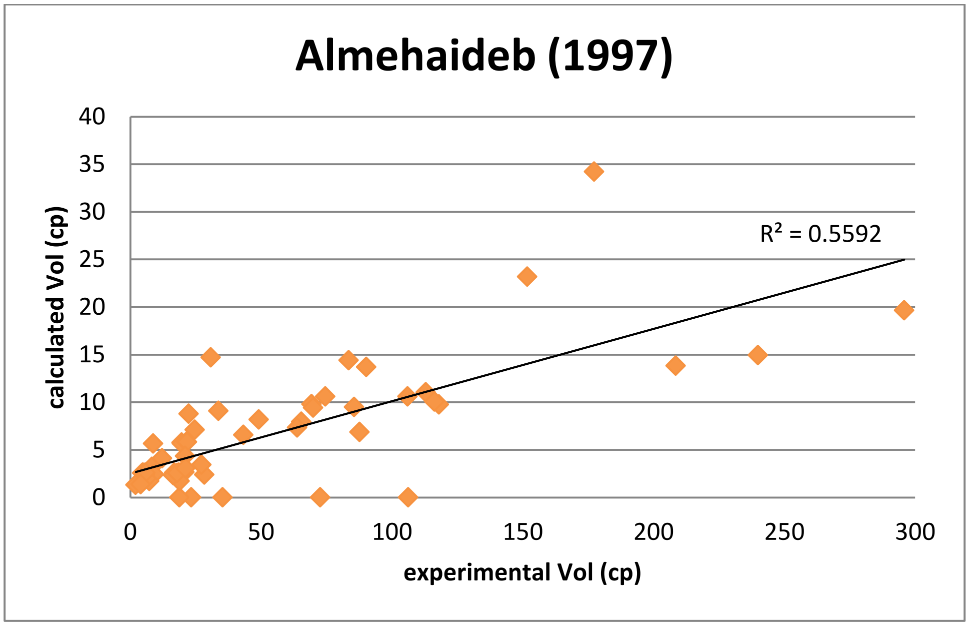


FIGURE 11. Almehaideb’s correlation for bubblepoint oil viscosity

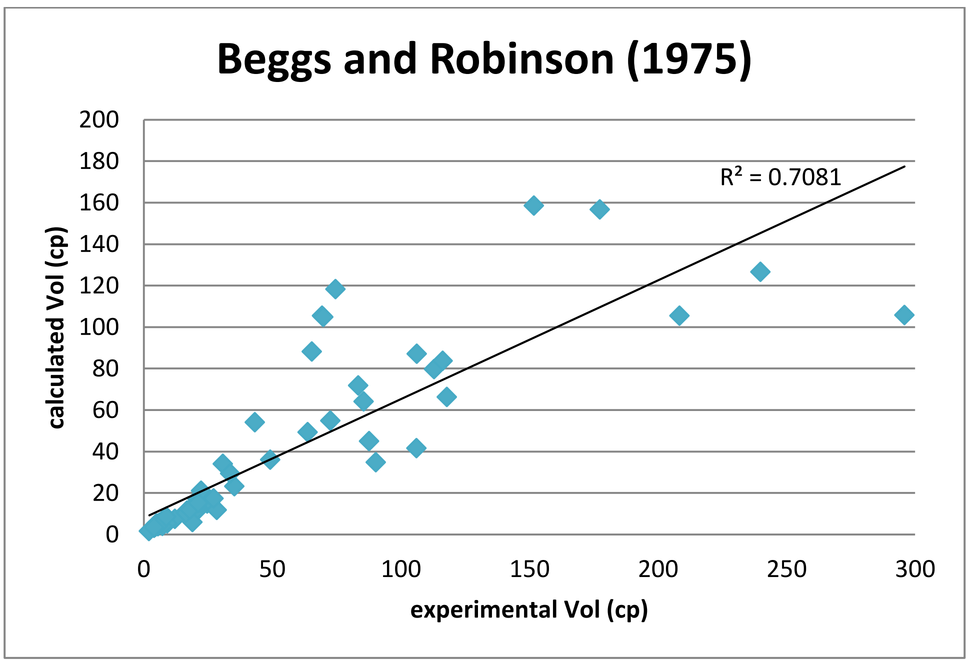


FIGURE 12. Beggs and Robinson’s correlation for bubblepoint oil viscosity

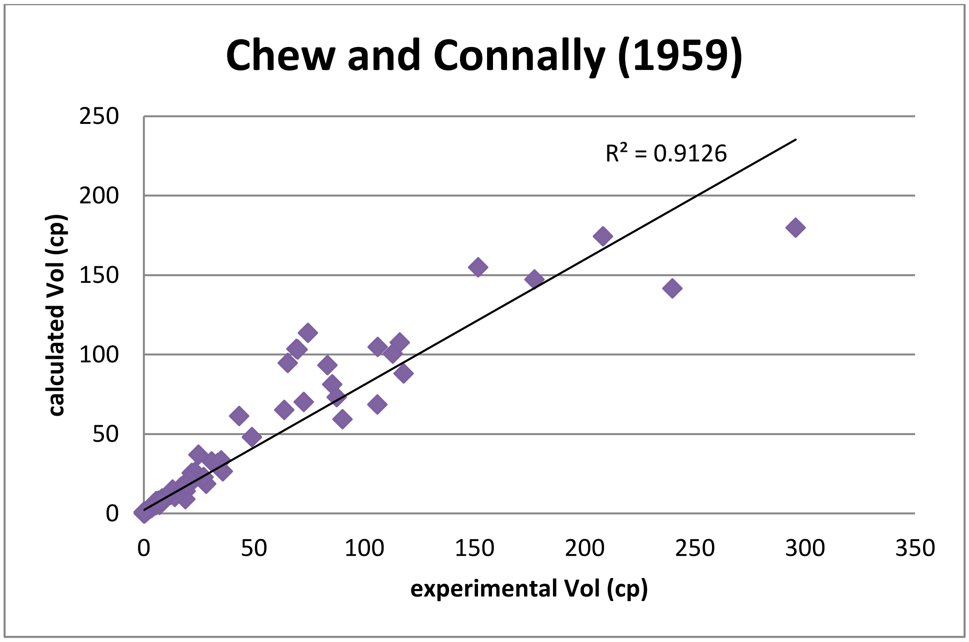


FIGURE 13. Chew and Connally’s correlation for bubblepoint oil viscosity

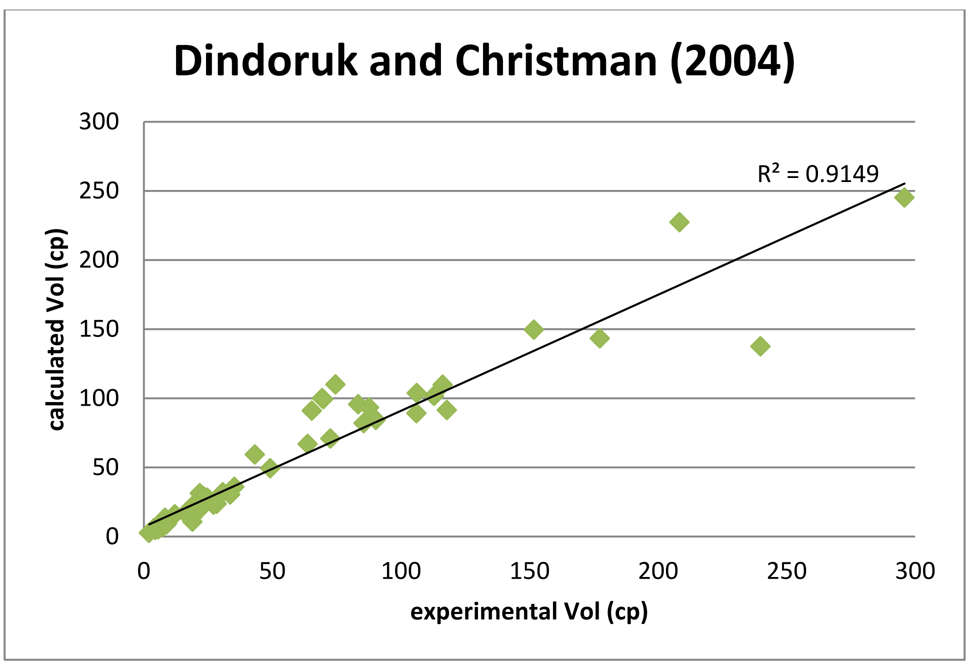


FIGURE 14. Dindoruk and Christman’s correlation for bubblepoint oil viscosity

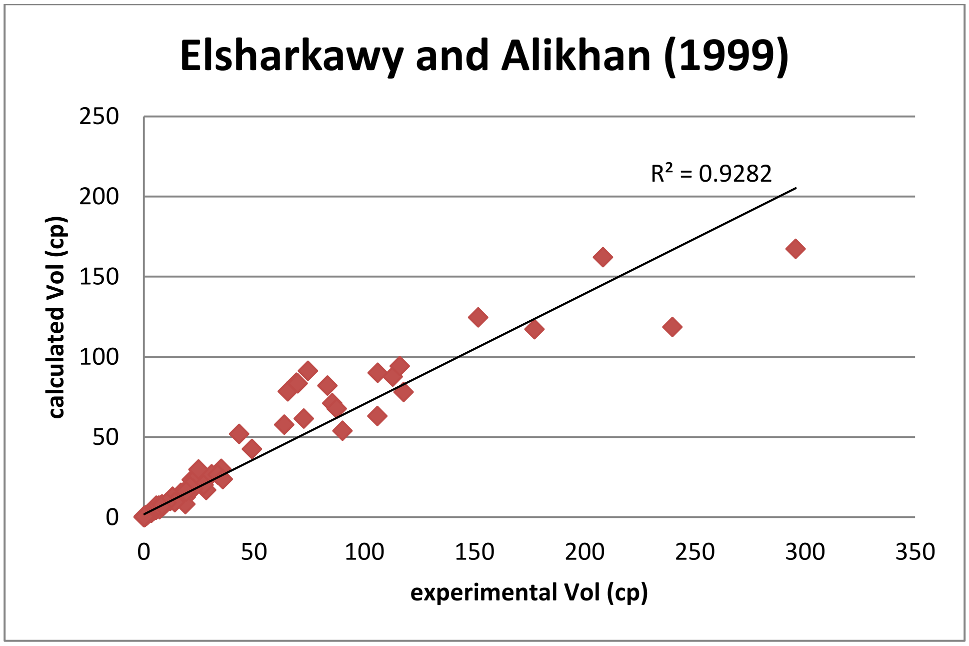


FIGURE 15. Elsharkawy and Alikhan's correlation for bubblepoint oil viscosity

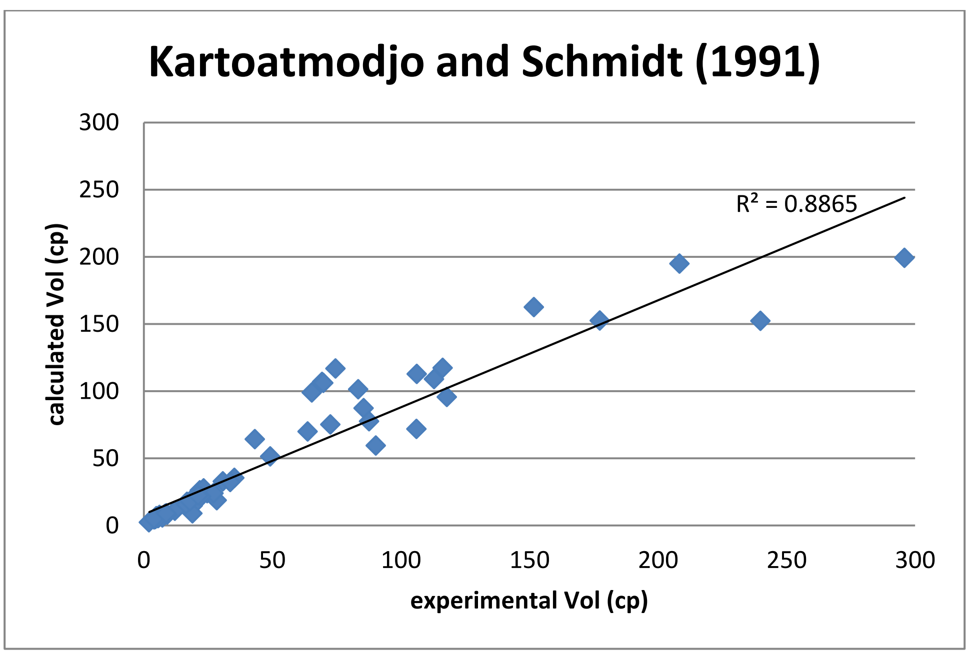


FIGURE 16. Kartoatmodjo and Schmidt's correlation for bubblepoint oil viscosity

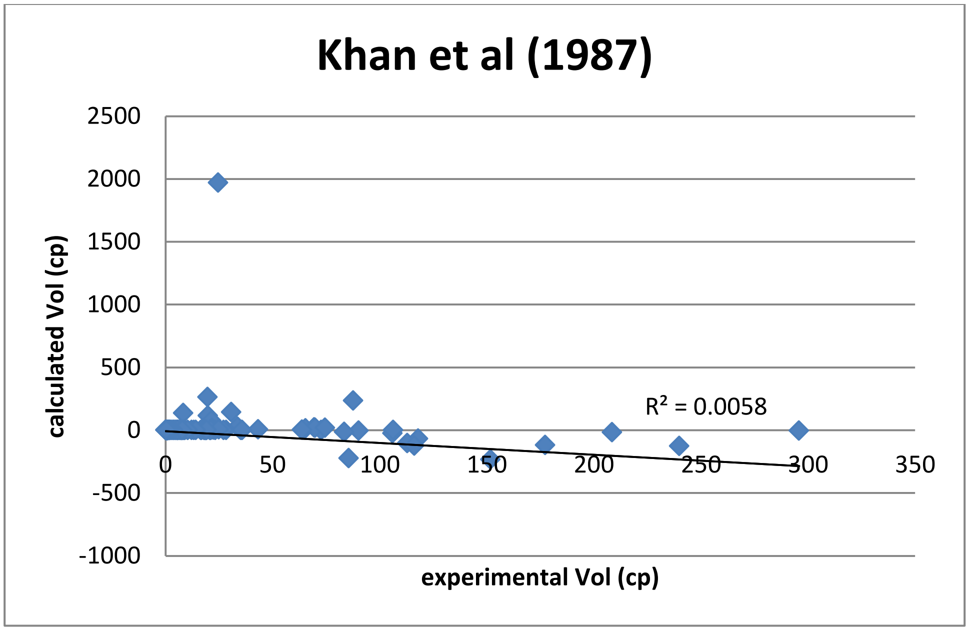


FIGURE 17. Khan et al’s correlation for bubblepoint oil viscosity

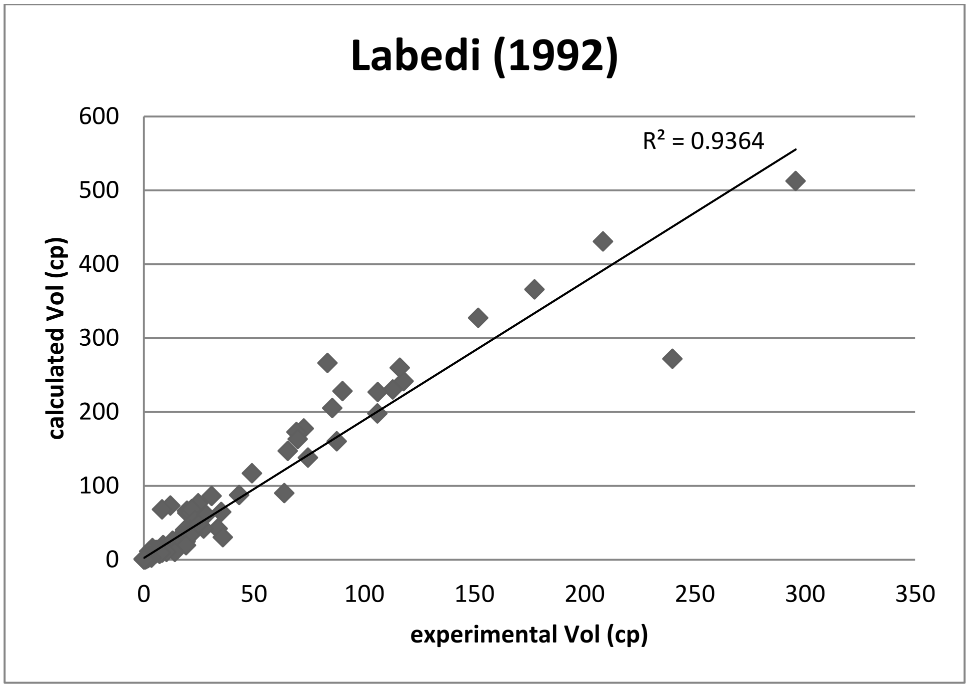


FIGURE 18. Labedi’s correlation for bubblepoint oil viscosity

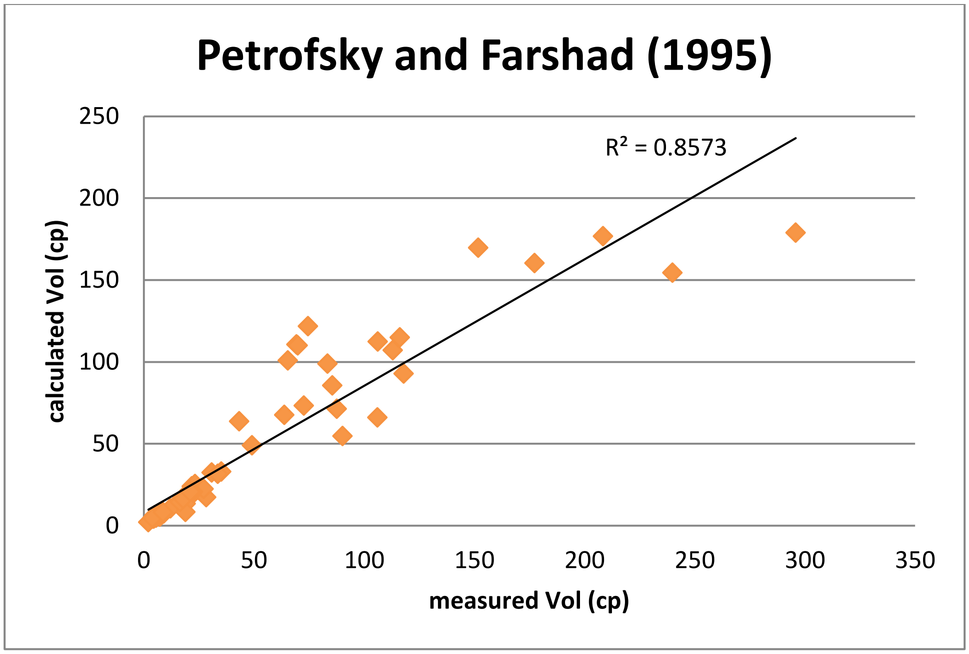


FIGURE 19. Petrosky and Farshad's correlation for bubblepoint oil viscosity

Undersaturated Oil Viscosity Correlations

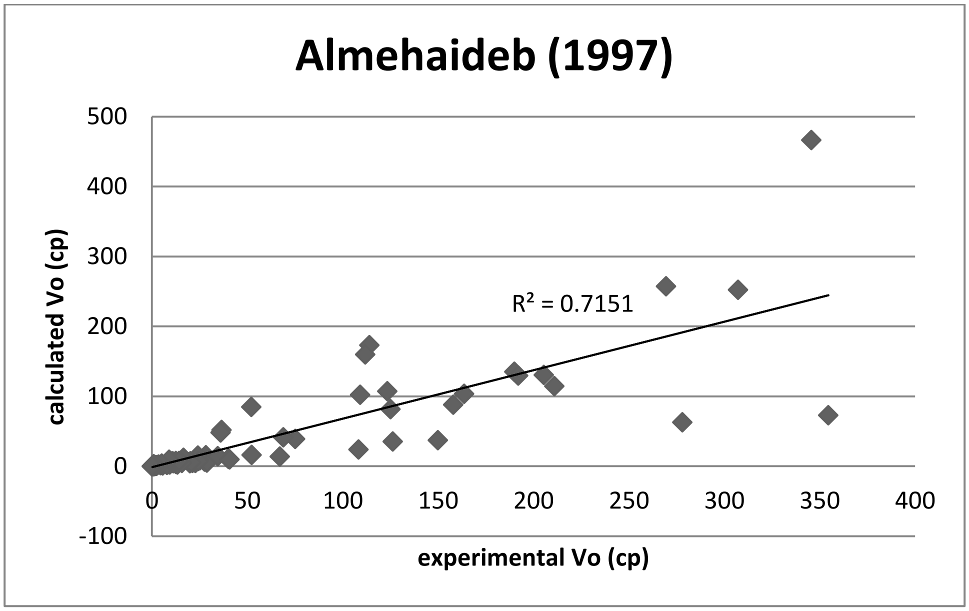


FIGURE 20. Almehaideb's correlation for undersaturated oil viscosity

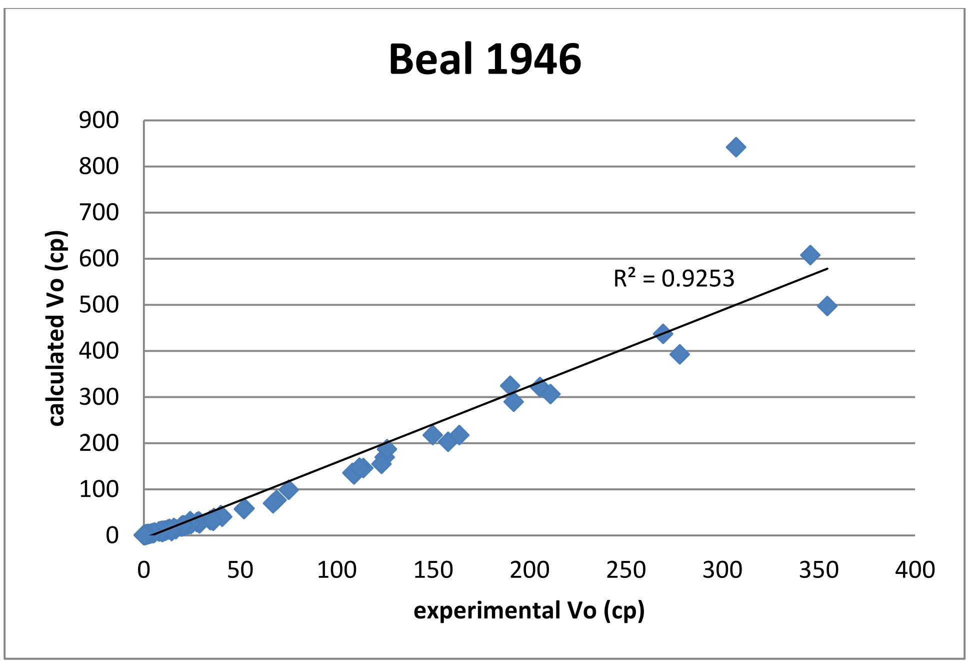


FIGURE 21. Beal's correlation for undersaturated oil viscosity

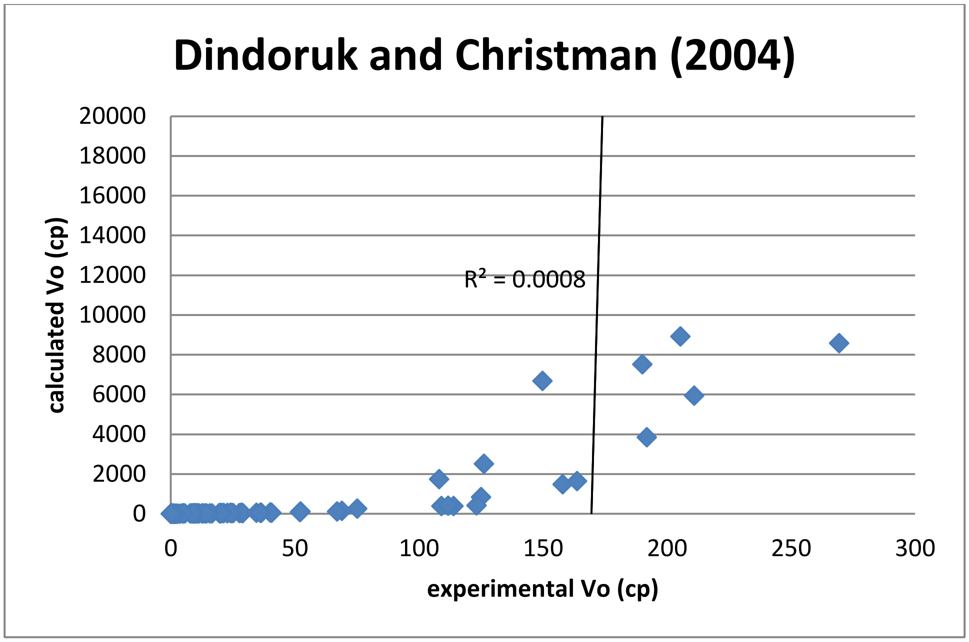


FIGURE 22. Dindoruk and Christman's correlation for undersaturated oil viscosity

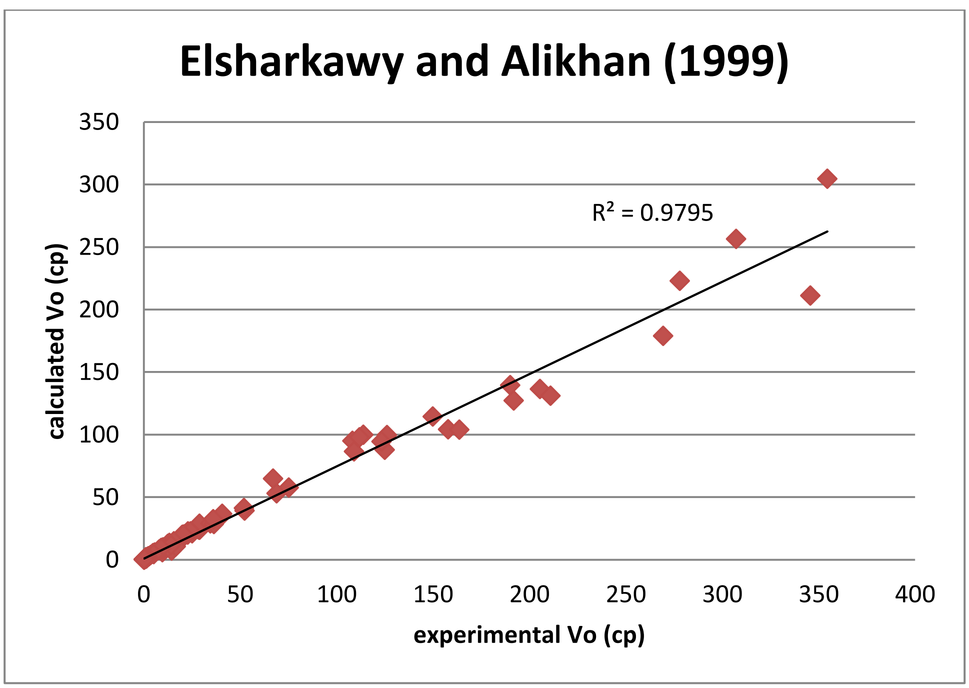


FIGURE 23. elsharkawy and Alikhan's correlation for undersaturated oil viscosity

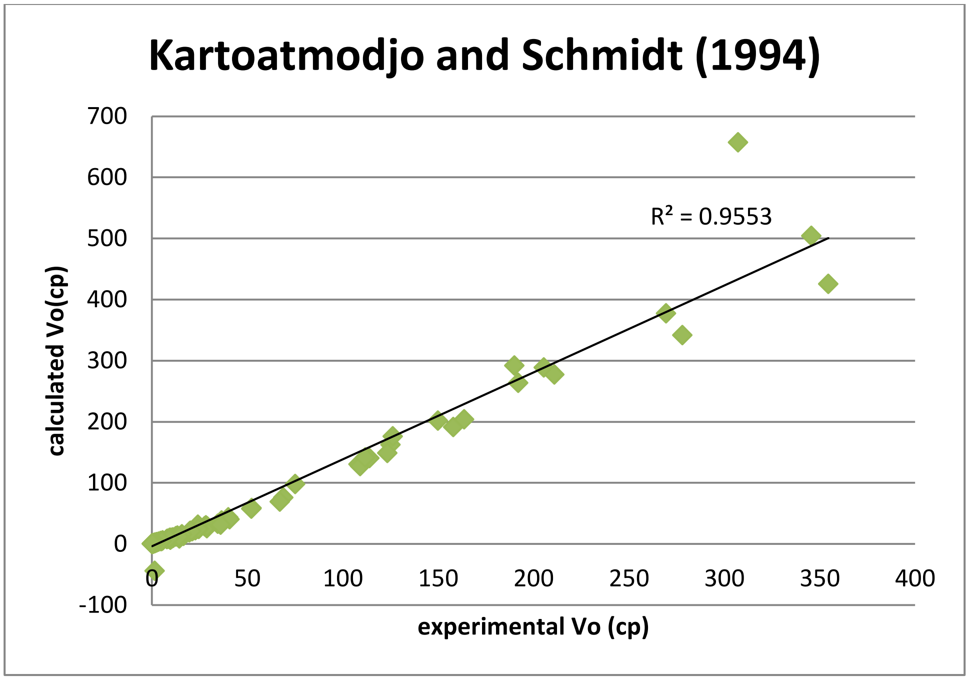
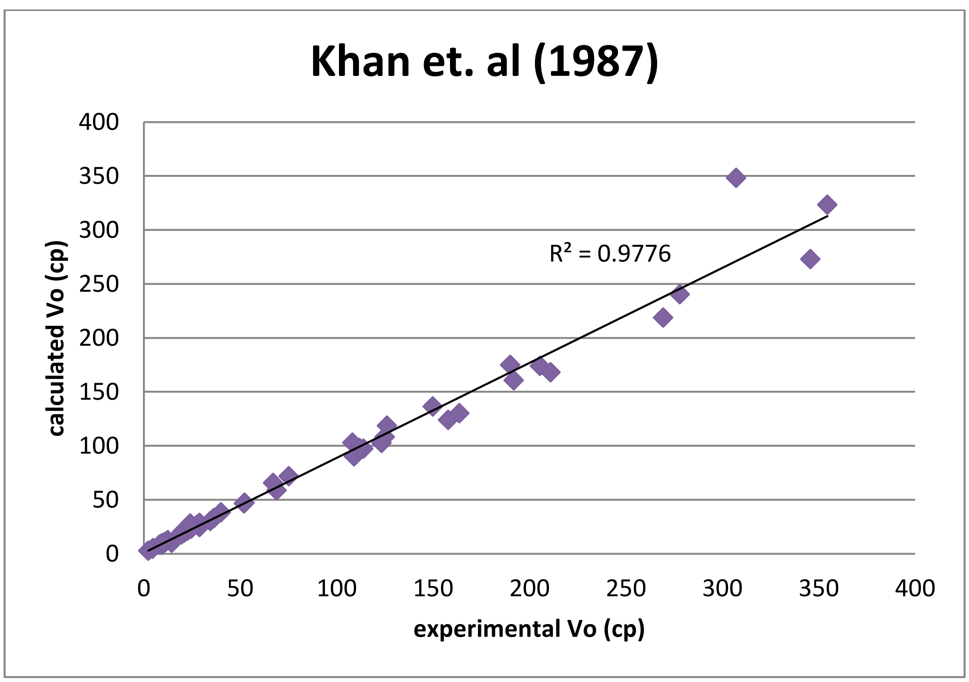


FIGURE 24. Kartoatmodjo and Schmidt's correlation for undersaturated oil viscosity



FI 25. Khan et al 's correlation for undersaturated oil viscosity

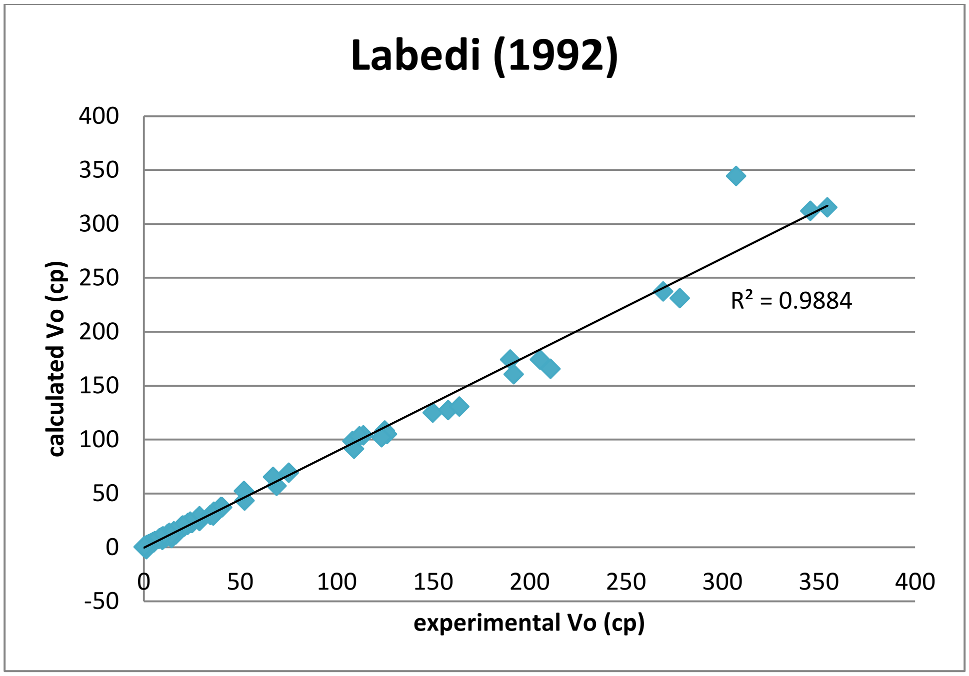


FIGURE 26. Labedi's correlation for undersaturated oil viscosity

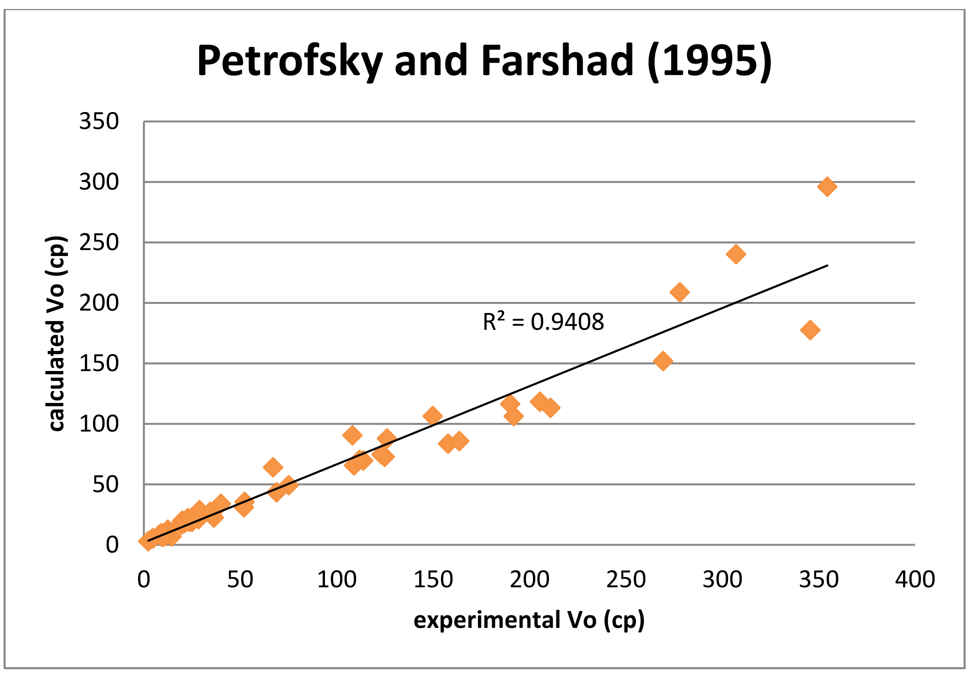


FIGURE 27. Petrosky and Farshad's correlation for undersaturated oil viscosity

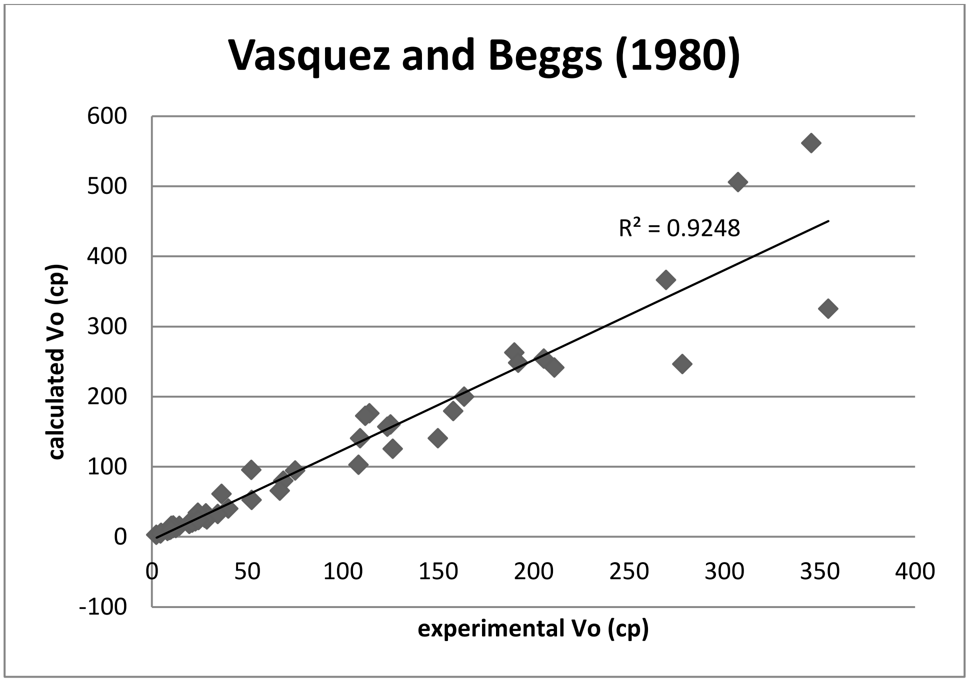


FIGURE 28. Vasquez and Beggs' correlation for undersaturated oil viscosity

4.2 RESULTS AND DISCUSSION

This project worked on the analysis of the most well-known correlations that has beeen described in literatures on predicting oil viscosity that have been applied in the industry. By applying the experimental measured PVT data from Table 6, the correlations is applied to estimate the oil viscosity of dead oil, bubblepoint oil and also undersaturated oil.

The study was carried out by using both graphical and statistical analysis. Diagrams of calculated viscosity versus the experimental viscosity were built for each of the correlations for each type of oil viscosities. The diagrams for each correlations tested are illustrated in Figure 2 until Figure 28.

Beside the graphical analysis with the diagrams, the study also carried out using the assistance of the **statistical analysis** to prove a point firmer. The statistical analysis is started by determining the **Relative Deviation** between the calculated value of the oil viscosities and the experimentally measured value of the oil viscosities. The relative deviation is defined as E_i ,

$$E_i = \left|\frac{C_i - M_i}{M_i}\right|$$

The statistical analysis is then followed by determining the **Average Arithmetic Error (AAE)**, and it is defined as E_m ,

$$E_m = \left(\sum_{i=1}^{N} \frac{E_i}{N}\right) \times 100$$

After having calculated both the Relative Deviation and Arithmetic Absolute Error for all the samples, the results is then subjected to an analysis of calculating the **Standard Deviation, SD** and it is defined as,

$$SD = \sqrt{\frac{\sum_{i=1}^{N}[E_i - E_m]^2}{N-1}}$$

The correlation providing the **smallest** $\boldsymbol{E_m}$ value is the best. If **equal** $\boldsymbol{E_m}$ is found for more correlations, **the lowest standard deviation** value is defined the best one.

The statistical analysis also carried out based on the **R-squared ($\mathbf{R^2}$) coefficient** displayed together with the scatterplots of each correlation in Figure 2 until Figure 28. In regression, the R^2 coefficient of determination is a statistical measure of how well the regression line approximates the real data points. In this study, an R^2 of 1 indicates that the regression line perfectly fits the data or in other words, the calculated value of oil viscosities using the correlations are perfectly match with the experimentally measured value of oil viscosities. The R^2 coefficient is to be considered in choosing the most accurate correlation if the values of AAE and SD are equal for more than one correlations. The correlation that has the value of R^2 coefficient that is closest to 1 will be chosen as the most accurate correlation compared to the other 8 correlations that have been selected for the comparison.

The results of the statistical analysis of the study are shown in Table 7, 8, and 9.

Table 7 shows the best results from the statistical analysis performed on Agip's sample by applying the correlations of **dead oil viscosity**. In terms of **extra heavy oils** and heavy oils with API ranging from less than 10 API for extra heavy oils, out of the 9 correlations selected for the comparison, the correlation from **Elsharkawy and Alikhan** produced the least average absolute error and standard deviation which is 0.003 percentage of error and 0.0002 respectively. On the other hand, Beal's correlation produced the largest average absolute error and standard deviation which is 71.55 percentage of error and 4.88 respectively. Furthermore, the value of R^2 coefficient from Elsharkawy and Alikhan's shows the largest value of 0.84 meaning that the correlation is the most accurate correlation compared to other correlations in predicting extra heavy dead oil viscosity. For **heavy oils**, with API ranging between 11 °API to 22.3 °API, the most accurate correlation out of the nine dead oil viscosity correlations is **Glaso's correlation** showing the least average absolute error of 0.0003 and standard deviation of 0.0002. Figure 5 and 6 show that **Glaso's and Elsharkawy and Alikhan's correlations** have the smaller scatter points around the trendline compared to other correlations.

The **saturated-oil or bubblepoint oil viscosity** is defined as the crude oil's viscosity at the bubblepoint pressure and reservoir temperature. Nine correlations in total have been selected in this study to compare and select the most accurate correlation to predict extra heavy and also heavy oil viscosities. Table 8 shows the best results from the statistical analysis performed on 195 data points of Agip's sample, dividing into 4 several API ranges. The bubblepoint correlations are applied on the samples and the average absolute error and the standard deviation are recorded to prove which correlation is the most accurate among the nine correlations selected. For **extra heavy oil** which API is less than 10 °API, the **Petrosky and Farshad's correlation** show the least average absolute error and standard deviation with the value of 7.12E-05 percentage and 4.86E-06 respectively. This mean that the correlation is the most accurate correlation in terms of extra heavy oil viscosity. In **heavy oil** catergory, from Table 8, it shows that **Chew and Connally's correlation** have the least average absolute error and standard deviation of 8.67E-06 percentage of error and 5.92E-07 respectively. Based on graphical analysis as shown in Figure 19 and 13, the **Petrosky and Farshad's and Chew and Connally's correlations** have the smaller scatter points around the trendline compared to other correlations.

Another category is the **undersaturated oil viscosity**. Table 9 show the best results from the statistical analysis performed on Agip's sample used in this study, showed in Table 6, by applying the undersaturated oil viscosity correlations selected for this comparison study. In the class of **extra heavy oil (°API < 10)**, it shows that correlation by **Elsharkawy and Alikhan** has the smallest average absolute error and standard deviatioin of 0.0037 percentage of error and 0.0003 respectively. This indicates that Elsharkawy and Alikhan's correlation is the most accurate compared to other correlations selected in this study to predict extra heavy undersaturated oil viscosity. In terms of **heavy oil (10< °API ≤ 22.3)**, several correlations showed the same value of average absolute error and standard deviation. In order to choose the most accurate correlation for heavy undersaturated oil viscosity, the R^2 coefficient has been taken acount into the decision making. Based on the R^2 coefficient of the correlations, the correlation by **Labedi (1992)** has the largest value which is 0.9884. The graphical analysis of the correlations, as shown in Figure 26, Labedi's correlation has the smallest scatter points around the trendline compared to other correlations. Hence, Labedi's correlation is the most accurate correlation in this study to predict heavy undersaturated oil viscosity.

°API Range	Author	Beal	Beggs and Robinson	Dindoruk and Christman	Elsharkawy and Alikhan	Glaso	Kartoatmodjo and Schmidt	Labedi	Egbogah and Jacks	Petrosky and Farshad
°API ≤10	AAE	71.55	0.38	0.11	0.003	0.85	1.61	1.45	0.23	0.82
	SD	4.88	0.03	0.01	0.0002	0.06	0.11	0.10	0.02	0.06
10< °API ≤ 22.3	AAE	3.25	0.18	0.02	0.02	0.0003	0.0005	0.01	0.004	0.002
	SD	0.22	0.01	0.001	0.001	0.0002	0.000036	0.001	0.0003	0.0002
22.3 < °API ≤ 31.1	AAE	1.19	0.47	0.02	0.03	0.0001	0.01	0.03	0.06	0.01
	SD	0.08	0.03	0.001	0.002	0.0002	0.0007	0.002	0.004	0.001
°API > 31.1	AAE	0.81	0.03	0.0007	0.0003	0.004	0.001	0.01	0.03	0.004
	SD	0.06	0.001	0.000048	0.00002	0.0003	0.000075	0.00045	0.002	0.0003
R^2		0.655	0.759	0.6827	0.8435	0.6583	0.6569	0.7263	0.8347	0.6939

TABLE 11. Best results of statistical analysis performed on Agip's samples for dead oil viscosity

°API Range	Author	Alme haideb	Beggs and Robinson	Chew and Connally	Dindoruk and Christman	Elsharkawy and Alikhan	Kartoat modjo and Schmidt	Khan et al	Labedi	Petrosky and Farshad
°API ≤10	AAE SD	0.34 0.02	0.02 0.001	0.01 0.0004	0.0002 1.41E-05	0.0085 0.00058	0.004 0.00026	0.51 0.03	0.07 0.004	7.12E-05 4.86E-06
10< °API ≤ 22.3	AAE SD	0.18 0.01	0.01 0.0007	8.67E-06 5.92E-07	0.0005 3.08E-05	0.0028 0.00020	0.0011 7.47E-05	0.11 0.01	0.12 0.008	0.006 0.0004
22.3 < °API ≤ 31.1	AAE SD	0.01 0.0003	0.01 0.0004	0.002 0.0002	0.0036 0.00025	0.0020 0.00014	4.43E-06 3.02E-06	0.40 0.03	0.002 0.0001	0.0005 3.21E-05
°API > 31.1	AAE SD	0.0005 3.4E-5	0.003 0.0002	0.005 0.0003	0.00039 2.62E-05	0.0015 0.00011	0.0007 4.44E-05	0.47 0.03	0.004 0.0003	0.0006 4.32E-05
R^2		0.5592	0.7081	0.9126	0.9149	0.9282	0.8865	0.0058	0.9364	0.8573

TABLE 12. Best results of statistical analysis performed on Agip's samples for bubblepoint oil viscosity

°API Range	Author	Alme haideb	Beal	Dindoruk and Christman	Elsharkawy and Alikhan	Kartoat modjo and Schmidt	Khan et al	Labedi	Petrosky and Farshad	Vasquez and Beggs
°API ≤10	AAE	0.023	0.0053	0.0042	0.0037	0.0039	0.0074	0.009	0.015	0.0078
	SD	0.0016	0.0004	0.0003	0.0003	0.0003	0.0005	0.0006	0.001	0.0005
10< °API ≤ 22.3	AAE	0.034	0	0	0	0.0003	0	0	0.0002	0
	SD	0.002	0	0	0	2.38E-05	0	0	1.49E-05	0
22.3 < °API ≤ 31.1	AAE	0.094	0	0	0	0.0004	0	0	0.002	0
	SD	0.006	0	0	0	2.83E-05	0	0	0.0002	0
°API > 31.1	AAE	0.0009	0	0	0	0.0004	0	0	0.001	0
	SD	6.4E-5	0	0	0	2.83E-05	0	0	9.07E-05	0
R^2		0.7151	0.9253	0.0008	0.9795	0.9553	0.9776	0.9884	0.9408	0.9248

TABLE 13. Best results of statistical analysis performed on Agip's samples for undersaturated oil viscosity

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The objective of this study is to compare the best correlation among the correlations selected to predict heavy oil viscosity. The correlations selected to be used in this study are the ones that have been introduced or applied before in the industry taken from the previous literature. The correlations also divided into 3 categories which is **dead oil viscosity correlations, bubblepoint or gas-saturated oil viscosity correlations and undersaturated oil viscosity correlations.**

The correlations were tested with a set of experimentally measured PVT data also referred from previous study. In this study, Agip's 195 oil samples have beed used to show the accuracy of the correlations hence select the most accurate correlation based on the analysis. The oil samples are collected from the Mediterranian Basin, Africa, Persian Gulf and North Sea. The PVT data includes API Gravity, Reservoir Temperature and Pressure, Bubblepoint Pressure, Gas-Oil Ratio, Gas Specific Gravity and also the experimentally measured value of dead oil, bubblepoint oil and undersaturated oil viscosities.

The objective of the study is achieved by applying the correlations with the oil samples and analyze the results graphically using diagrams and also statistically with aid of Relative Deviation, Average Absolute Error (AAE), Standard Deviation and R^2 coefficient.

Based on the analysis performed on the oil samples using the correlations selected for this study, it has been divided into 3 categories of dead oil, bubblepoint oil and undersaturated oil. It also focused on the extra heavy oil (°API < 10) and heavy oil ($10<$ °API ≤ 22.3) samples.

Several correlations or empirical models that have been used for estimating the heavy oil viscosity using Agip's oil samples collected from Mediterranian Basin, Africa, Persian Gulf and North Sea. It was found that some of the published models especially the ones that are used in this study do not accurately predict the viscosity of dead oil, bubblepoint oil and undersaturated oil. Some of them predict with a small error and some of them predict the viscosities with huge error.

Based on graphical analysis, as shown in Figure 3 and 4, Beggs and Robinson (1975) and Dindoruk and Christman (2004) correlations show the largest scatter point around the trendline compared to other correlations of dead oil viscosity. Khan et al. (1987) correlation for bubblepoint oil viscosity showed an erratic prediction when tested using the Agip's oil samples as shown in Figure 17. The trendline is decreasing as the calculated viscosities for extra heavy oil predicted gave negative values of viscosities. For undersaturated oil, Dindoruk and Christman (2004) showed the largest scatter points around the trendline as in Figure 22. The R^2 coefficient of the graphical analysis showed the lowest value compared to others.

This study also proved that the selected correlations have limited accuracy when they are applied to predict viscosity of the oil samples for Agip's oil samples, as in Table 6, that were collected from several fields. Some of the models were developed from other regions with certain and limited data available. Correlations by Petrosky and Farshad (1995) have been developed using the crude oil samples collected from Gulf of Mexico [18] whereas the dead oil viscosity correlation by Beal (1946) was developed large data points collected from 492 oil fields in the United States [27]. Another correlation developed from the Gulf of Mexico is the correlations by Dindoruk and Christman (2001) [31].

In conclusion, in this study, a correlation has been proven that it is more accurate that others or in other words, produced smallest errors in both graphical and statistical analyzation.

5.2 RECOMMENDATION

The evaluation of the properties of the fluid has plays a a very significant role in the design of several surface facilities and also reservoir engineering studies. The development of correlations in predicting the fluid properties based on readily available measured parameters in the field itself has been under the spot light of investigationi for over forty-five years [32].

This study focused on the accuracy of published correlations on previous literatures on estimating the heavy oil viscosity. Viscosity is one of the most signficant physical properties and also a critical parameter that is required in various field of petroleum engineering analysis. These models were developed based on measured data on reservoirs or oil fields and are used in the industry when the parameters are not available. The correlations developed by previous researches are proven to predict the oil viscosity not accurately because of several reasons. One of the reasons is that not all correlations are geological applicable or can be used universally to any oil fields or reservoirs. This kind of reason is the one that limit the capability and the dependance of the correlations in predicting the oil viscosity especially heavy oils.

Artificial Neural Network (ANN)

Several researches have been done to improve the disadvantage of using correlations or empirical models to estimate oil viscosity. One of the method that has been intoduced is Artificial Neural Network. Artificial Neural Networks are parallel-distributed information procssing models that can recgnize highly complex patterns within the available data. In other words, it is a computer models that try to mimic simple biological learning process and simulate specific functions of human nervous system [33]. This Artificial Neural Network (ANN) has several advantages over the empirical models or correlations. Firstly, ANN learns the behaviour of the database population by self-tuning the parameters using a specific method that the trained ANN matches the employed data accurately. Another advantage is that the ANN gives a rapid and highly confident prediction of oil viscosity as soon as a new case is applied.

Genetic Algorithms

Another applicable and efficience method to estimate the heavy oil viscosity is by using genetic algorithms technology in petroleum engineering. Genetic algorithms are adaptive methods that may be used to solve and optimize problems [4]. In a study that focused on using genetic algorithms in viscosity prediction, the proposed model used 4 parameters as inputs which are pressure, temperature, reservoir fluid gas oil ratio and oil density. The ouput parameter is fluid viscosity. Table 10 shows the fitness and R^2 values for the performance of the genetic algorithms systems in viscosity prediction.

Training fitness	0.004068
Validation fitness	0.003963
T & V fitness	0.004015
Test fitness	0.045723
Training R^2	0.99913
Validation R^2	0.99742
T & V R^2	0.99828
Testing R^2	0.99742

TABLE 10. Fitness and R^2 values for training , validation and testing of genetic algorithm [4]

In a nutshell, nowadays, there are many other better methods that outperformed the existing correlations. The objectives of good viscosity prediction can be achieved by applying the most suitable methods or applications in the right situations or conditions.

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APPENDICES